SHIP BASED WEATHER ROUTEING

(Using Dynamical Meteorology)

by

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ABSTRACT

The relevance of ship based routeing is discussed. Data collected at sea are analysed to produce vessel response characteristics Meteorological data are analysed in a conventional manner to establish effective steering criteria with respect to 500 mb flow.

For the first time a routeing model is formulated which recognises the three spatial dimensions of a middle latitude storm. A theoretical analysis of relative flow in a growing baroclinic wave is undertaken. Reference to displacement of the wave trough affords a measure of both storm development and steering effectiveness.

Short, medium and long term planning elements are combined in a model. The effectiveness of this approach is demonstrated by actually "weather routeing" a vessel, whilst comparing progress of a sister ship navigated conventionally. Sources of error and limitations of the model are discussed.

"My daily life at sea allows
me to test the laws which
closet philosophers are
elaborating on shore.
There is no such thing as
a really circular gale".
Master Mariner JINMAN (1861) (*64*)

Symbols and abbreviations are explained as they arise in the text.

References are numbered in parentheses using italics, thus: (*13*)

DECLARATIONS

- as required by CNAA regulations p. 23 para. 7

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other CNAA or University award.

None of the material herein has been used in any other submission for an academic award.

RELATED OUT-OF-COLLEGE CONFERENCES AND SEMINARS UNDERTAKEN AS PART OF CURRENT RESEARCH BY CAPT. R. MOTTE

1. February 19 1980	One day Conference at INSTITUTE OF MARINE ENGINEERS, Mark Lane, London. "OPERATION OF SHIPS IN ROUGH WEATHER" Contribution on Weather Routeing of Ships. (*80*)
2. June 9-12 1980	Seminar on "Weather and Sea State for N. Atlantic and North Sea" B.P. SHIPPING LTD., Brittanic House, Moorlane, London. 1. Chairman of Seminar 2. Contribution on Baroclinic Waves and Single Station Forecasting
3. November 24-27 1980	Seminar on "Weather and Sea State for North Sea" B.P. SHIPPING LTD., Brittanic House, Moorlane, London. 1. Chairman of Seminar 2. Contribution on use of Facsimile data for forecasting
4. March 9-11 1981	Seminar on "Weather Routeing of Ships" DART CONTAINERS LTD., Tolworth Towers, London. 1. Chairman of Seminar 2. Contribution on "Weather Routeing Techniques" (*21*)

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formulae

2(i)	$C^2 = \frac{gL}{2\pi}$
2(ii)	$L = 2\pi C^2/g = gT^2/2\pi$
2(iii)	$T = (2\pi L/g)^{1/2} = 2\pi C/g$
2(iv)	$C = L_s/t \pm V_s$
2(v)	$T = \frac{C\Delta t \pm V_s \Delta t}{C}$
2(vi)	$R_e = Vl/K$
2(vii)	$R_e = \frac{u_* Z_o}{K} > 5$
2(viii)	$C(V-C)^2 = \frac{4Kg(\rho-\rho')}{S\rho'}$
2(ix)	$Z_0 = \frac{1}{50}\frac{u_*^2}{g}$
2(x)	$S(t) = \sum_{i=1}^{N} a_i \cos(\omega_i t + \alpha_i)$
2(xi)	$E = \frac{1}{2} a^2 \rho g b \lambda$
2(xii)	$S_\zeta(\omega)/H_{1/3}^2 = \alpha/\omega^5 \exp\left(\frac{-4\alpha}{\omega^5}\right); \quad \alpha = \frac{124}{T_z^4}$
2(xiii)	$S_\zeta(\omega,\mu) = \left(\frac{2}{\pi}\cos^2(\mu-\bar{\mu})\right)\cdot S_\zeta(\omega)$
2(xiv)	$H = 0.48V$
2(xv)	$L = 10.62H^{4/3} = 3.55V^{4/3}$
2(xvi)	$H = 0.44V$
2(xvii)	$H = 0.026V^2$
2(xviii)	$H = 0.3V^2/g = 0.0305V^2$
2(xix)	$H = (E/K)^{1/2}$
2(xx)	$S_\zeta(\omega) = \frac{8.39}{\omega^5}\exp\left(\frac{-9.76\times10^4}{\omega^4 V^4}\right) \text{ft}^2\,\text{sec}$
2(xxi)	$H = 0.0185\,V^2$
2(xxii)	$H = 0.075(1-\exp(-0.047F))V^{3/2}$
2(xxiii)	$H = 0.075V^{3/2} + H_S$
3(i)	$V_c = A/(\sin 1)^{1/2}\cdot V$
3(ii)	$V_c = 0.015V/(\sin 1)^{1/2}$
3(iii)	$\bar{R}_{AW} = 2\int_0^\infty R_{AW}/\zeta_a^2 \cdot S_\zeta(\omega)\cdot d\omega$
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3(v)	$V_{est_1} = 19.87 + 6.38(\ln P - \ln 20{,}000) - 10.2\frac{V}{P}H_w^2$ $[\cos^3(\mu/2)+0.3) + 0.04(\theta-12) - 0.00015(\Delta-37000) \pm 0.28$
3(vi)	$V_{c_2} = V_{ch_{c1}} + 10.2\frac{VH_w^2}{P}(\cos^3(\frac{\mu}{2})+0.3) - 0.04(\theta-12) + 0.00015(\Delta-37000)$
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3(viii)	$V_{c_2} = V_{ch_{c2}} + 10.2\frac{VH_w^2}{P}(\cos^3(\frac{\mu}{2})+0.3) + 0.28\frac{V^3}{P}[(\frac{V_R}{V})^2\cos\beta - 1] - 0.04(\theta-12) + 0.00012(\Delta-37000)$
3(ix)	$V_{est_2} = 6.44\ln P - 43.85$
5(i)	$\frac{Du}{Dt} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0$
5(ii)	$u = fy \quad (v = Dy/Dt)$
5(iii)	$M_2/M_1 = \theta_1/\theta_2$
5(iv)	$\Delta P.E. = M_1 g (Z_2 - Z_1)\left(\frac{\theta_1-\theta_2}{\theta_2}\right)$
5(v)	$\Delta K.E = \frac{1}{2}M_1\underset{\sim}{V}^2 + \frac{1}{2}M_2\underset{\sim}{V}^2 = \frac{1}{2}M_1\left(1+\frac{\theta_1}{\theta_2}\right)\underset{\sim}{V}^2$
5(vi)	$\underset{\sim}{V} = \left(\frac{g\,\Delta Z\,\Delta\theta}{\bar{\theta}}\right)^{1/2}$
5(vii)	$\frac{D\zeta}{Dt} + V\beta = f\frac{\partial w}{\partial z} + \frac{fw}{\rho}\frac{\partial\rho}{\partial z}$
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5(ix)	$\partial/\partial z\left(\frac{\partial\tau_y}{\partial x} - \frac{\partial\tau_x}{\partial y}\right) = +f\frac{\partial(\rho w)}{\partial z}$
5(x)	$(\rho w)z = 1/f\left(\partial\tau_y/\partial x - \partial\tau_x/\partial y\right)$
5(xi)	$\zeta_{parcel} = \zeta_0 \exp(-k\rho t/\bar{\rho}H)$
5(xii)	$u = \bar{u} + u'$
5(xiii)	$\bar{u}_T = \frac{g}{f\bar{T}}\frac{dT}{dy}$
5(xiv)	$L^2 = 4\pi\bar{u}/\beta$
6(i)	$r = 2R\tan\alpha/2$
6(ii)	$2\frac{\sin\alpha/2}{\cos\alpha/2}\cdot\frac{1}{2\sin\alpha/2\cos\alpha/2} = \sec^2\alpha/2$
6(iii)	$dr/R\,d\alpha = 2R/R\,\frac{1}{2}\sec^2\alpha/2 = \sec^2\alpha/2$
6(iv)	$x_1 = x_{1_h} + \frac{r}{d_o}\sin(\theta-\frac{\pi}{6}); \; x_2 = x_{2_h} + \frac{r}{d_o}\cos(\theta-\frac{\pi}{6})$
6(v)	$\theta = \arctan((x_1 - x_{1_h})/(x_2 - x_{2_h})) + \frac{\pi}{6}$
6(vi)	$\cos(\theta-\theta_0) = -(\tan\alpha\tan\alpha_0)^{-1}$
6(vii)	$r = r_1\exp(k(\theta-\theta_1))$
6(viii)	$\frac{dx_1}{dt} = V(t,x_1,x_2,p)\cos p + S_1(t,x_1,x_2); \; \frac{dx_2}{dt} = V\sin p + S_2$
6(ix)	$\frac{dx_i}{dt} = f_i(t,x,u)$
6(x)	$x_i(t_0) = x_{i_0},\; x_i(t_1) = x_{i_1}$
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6(xii)	$\frac{d\lambda_2}{dt} = -\sum_{i=1}^2 \lambda_i(V_{ix_2} + S_{ix_2})$
6(xiii)	$\sum_{i=1}^2 \lambda_i V_{ip} = 0$
6(xiv)	$\sum_{i=1}^2 \lambda_i(V_i + S_i) = \lambda_0 > 0$
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6(xvii)	$V^2 + 2V_p^2 - VV_{pp} \neq 0$
6(xviii)	$V_{x_i}(i,j) = \frac{1}{2}(V(i+1,j) - V(i-1,j))$
6(xix)	$\frac{dx_0}{dt} = f_0(t, x_1, x_2, V, p)$
6(xx)	$\frac{dx_1}{dt} = V\cos p + S_1(t,x_1,x_2); \; \frac{dx_2}{dt} = V\sin p + S_2(t,x_1,x_2)$
6(xxi)	$\int_0^{t_1} f_0(t,x_1,x_2,V,p)\,dt$
6(xxii)	$-f_{0V} + \lambda_1\cos p + \lambda_2\sin p = 0$
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6(xxiv)	$\cancel{V}\, f_0(t,x_1,x_2,V,p)$

R.M.

INTRODUCTION

There would be no problem in planning a vessel's route across an ocean if it was possible to forecast with total accuracy the actual sea state existing for the duration of a voyage. Such an ideal circumstance is not as yet possible, therefore a modified technique is adopted in order to give a good indication of likely conditions. A system of storm avoidance is outlined which requires a knowledge of the structure, energetics and behaviour of middle latitude depressions. Consequently a four dimensional analysis is undertaken of a growing baroclinic wave and a case study of depression behaviour is included both for winter and summer instances in the North Atlantic Ocean. The relationship between wind velocity and generated sea state is considered and several established relationships compared. A ship speed analysis exercise is included commencing with data collected from vessels on ocean passages (S.T. Gondwana, a steam turbine V.L.C.C. and M.V. Dart Atlantic, a container ship). These data are analysed and ship performance curves produced relating speed of vessel to relative sea state.

The production of least time tracks is considered from basic optimal control theory as used by some shore routeing agencies. A ship based model is formulated based on a storm avoidance technique using short, medium and long term data to assist in decision making. Two sister container ships are routed during the month of February across the North Atlantic on west bound passages. One of the vessels uses the methods outlined, the other is unrouted and the actual routes are compared.

This work represents the culmination of some thirteen years continuous practical seafaring experience from midshipman to shipmaster serving on thirty different deep sea vessels of various size and type, reinforced with some twelve years of academic endeavour in meteorology. Hopefully an effective combination of these two experiences is brought to fruition in this document.

1. HISTORY AND EVOLUTION OF WEATHER ROUTEING

1.1 Weather Routeing

1.1.1 The Principle

The term "Weather Routeing" is itself a misnomer; in fact it is the ship that is routed. However, this term is in common usage and is incorporated together with the American spelling "routing" in current literature.

In the days of sail, ships were "weather routed" by their Masters with a vast amount of knowledge and skill based almost purely on experience and personal observation. When the steam ship arrived on the scene, ships simply steamed on into whatever seas they encountered at whatever speed the engine would provide: this was the advantage of steam over sail. The main reason for this was that it was not possible with any degree of certainty to determine what weather lay ahead. The collection and analysis of oceanographical and meteorological data has made enormous advances in recent years,now the ship's officer can be provided with up-to-date synoptic and forecast charts with no more effort than turning a dial. The real effort comes in correctly interpreting the information so received.

As shipping operations become more sophisticated, it can be expected that weather routeing of ships will become a major economic factor in ship operation. This will be extended to all parts of the world as services such as World Weather Watch expand. A realisation of the potential which optimum track routeing of ships provides is essential.

Strictly, "optimum track" refers to the "least time track" between two ports. The term "strategic track" can be used when requirements other than time are paramount. The "advised" route covers both of these terms when a ship is being routed and priorities have been specified.

The actual route selection is a subjective choice depending upon the route operator's experience and the special requirements of the shipowner or shipmaster. It is possible to introduce the several variables of ship performance, marine environment and constraints of the operator into a computer model as a dynamic control process of a stochastic nature. This will be discussed in 6.

Weather routeing is an application of meteorological and oceanographical data extrapolated to give a forecast for the most favourable route for ocean crossing by surface vessels. An optimum time track is estimated originally and modified from weather surveillance throughout a voyage as appropriate to existing and forecast conditions.

This concept is founded in the belief that we can describe existing conditions and forecast future changes with sufficient accuracy to provide routeing superior to that based on climatology and to the practice of taking the shortest distance track.

Thus the advised route must offer a high probability of either a least steaming time route and/or the most favourable weather in the zone in question.

1.1.2 Objectives of Ship Routeing

The route which may be considered as optimum by ship operators at a given time depends on the ability of the ship and her cargo to sustain weather and seas, the urgency of her time schedule, and operational plans while under way.

Objectives of ship routeing may be summarised as follows:

(1) To minimise storm damage to ships and cargo, thereby to provide a safe passage.

(2) To save time at sea, thereby saving money by reducing operating time.

(3) To attain punctuality, essential for tidal terminals or to meet schedules. (Container terminals are similarly expensive investments and should not be allowed to stand idle.)

(4) To meet special requirements of the individual voyages. (Passenger comfort, etc.)

Requirements vary according to ship type with the implication of the saving of time within acceptable conditions. In cruise ships, passenger ships and troopships, passenger comfort and safety consistent with arriving on schedule are the main requirements.

For ships with sensitive cargo the schedule is of little importance compared with safe arrival of the cargo. A Master of a North Atlantic container ship will pay little attention to comfort of passage; time is all as long as the safety of his ship is not jeopardised.

Large modern vessels, such as the two or three hundred thousand tonne tankers, are constructed partly of high tensile steel which is susceptible to distortion or fracture under vibrational stresses. In extremes of weather these giants have to reduce to less than half their service speed to avoid possible structural damage. It would be preferable to avoid or minimise the effects of bad weather in the first instance by judicious route planning.

In practice more than one of the above objectives may be required which allows for the development of an algorithm computer model incorporating the several objectives and the response characteristics of the vessel.

1.2 Historical Appraisal of Routeing

1.2.1 Historical Synopsis

There is evidence to suggest that the present and the immediate past generations of mariner have lost the intimate knowledge that our forefathers had developed in understanding the behaviour of the atmosphere and the surface of the sea. These men had a depth of weather expertise and a knowledge of the oceans unparalleled by their successors.

Illustrated by Professor F. LUDLAM (*64*):

> "Progress in meteorology in the first half of the nineteenth century, leading to the cyclone flow models of Fitzroy and Jinman had been stimulated by mariners who had organised the accumulation of weather observations, partly to discover the laws of storms and rules to recognise their approach and avoid their dangers, and partly to produce climatic normals with which to plan the most economical routes". (Admiral

FITZROY and JINMAN, a Master Mariner of the Merchant Marine.)

From this early information the seasonal climatological atlas of "Ocean Passages for the World" was produced, based on Admiralty charts of oceanic currents, sailing directions and pilots, charted ice limits, and incorporating personal navigating notes of many ship masters for the trade routes with which they were best acquainted. This tome was the bible of the clippers and square-riggers of the late nineteenth and early twentieth centuries. Because of their inability to sail closer to the wind than say six points ($67\frac{1}{2}^{o}$) off either bow, a knowledge of likely prevailing winds was essential to a ship master when his only motive power was achieved through the agency of canvas.

Much of the earlier efforts were based on understanding of storms. In July 1687 WILLIAM DAMPIER (*64*), an English seaman, had fully recognized that the tropical storms of the Atlantic and Pacific are of the same species. "For my part I know no difference between a hurricane among the Caribee Islands in the West Indies and a Tuffoon on the coast of China or in the East Indies, but only the name".

In its very crudest form, weather routeing of ships is a very old art. In 1769 Benjamin Franklin, then Postmaster General of the U.S., advised mail ships to sail to Europe on the northern route and return on the southern route in what was later called the North-east Trade Wind zone. These route recommendations were based on, amongst other things, observations of the Gulf Stream, supplied by Franklin's Massachusetts whaling master kinsmen, enabling him to construct climatological charts.

In the early nineteenth century Redfield, an American naval architect, and Piddington, an English seaman, studied the depressions of the Atlantic and the cyclones of the Indian Ocean respectively and formulated the basis for a law of storms.

MATTHEW FONTAINE MAURY (69), added to the body of marine environmental knowledge by perusing ships' log books and recording valuable wind and current data.

In 1869 H.M.S. BRISK was anchored at the mouth of the English Channel as a storm warning vessel. She was intended as a forerunner to a trans-Atlantic cordon of ships at intervals of five hundred miles, in telegraphic communication with each other and the land. After six weeks the project was abandoned as inefficient and costly.

In 1882 the Meteorological Council of the Royal Society organised a vast undertaking to produce a set of "daily synchronous charts" for the North Atlantic, for a thirteen month period. Data were obtained from three thousand ships giving an average of seven hundred observations per day on which to base each chart. From these charts many of the original principles of weather knowledge were formulated.

With the advent of wireless telegraphy capable of spanning the Atlantic, a service was promoted under the auspices of the "New York Herald" to cable to the United Kingdom the departure of storms travelling eastward from the U.S.A., giving predictions on the track. On this side of the Atlantic, after a period of testing, it is not surprising that a decision was made to ignore such information as misleading.

The turn of the century heralded the passing of sail (commercially) and an era of combatting the elements by sheer power began. The machine had obviated the requirement of understanding weather processes. When the wind was the sole driving force it was necessary to bend rather than combat. Responses to weather extremes appear to have been reduced to a role of passive acceptance, the only practical steps being taken in extreme conditions such as avoiding tropical storms.

Great circle sailing was now the mainstay of the ship operator, although a modified version of "Ocean Passages for the World" was produced for steam ships in 1923, ADMIRALTY H.O. (*3*). The great circle technique prevailed because no accurate alternative system was available.

Since the introduction of radio weather bulletins for shipping after the First World War, the shipmaster has been able to practise an elementary form of weather routeing by the reception of coded messages on board ship. Since 1948 parts IV, V and VI of the International System of Weather Messages, with reports from ships, shore stations and the Atlantic weather bulletin, have been available, METEOROLOGICAL OFFICE (*74*).

The main centres of activity: depressions, troughs, anticyclones, ridges, are given together with co-ordinates of fronts and isobars at about 8 mb intervals. An analysis chart is constructed from this information. This method suffers from the disadvantages that:

(1) The construction of weather charts from coded radio bulletins is very time consuming, even when undertaken by an experienced officer.

(2) It can only present a superficial picture of the meteorological situation, as the number of co-ordinates is limited.

(3) Transmission by radio telegraphy is necessarily amplitude modulated and is subject to atmospheric interference.

(4) The time interval spanning construction, coding, transmission, reception, decoding and eventual use, often invalidates the limited picture available.

The Admiralty produce many fine seasonal charts of oceanographical and meteorological data (notably wind speed and direction information), generally on a seasonal basis. Now mean monthly charts of data are produced both by the U.S. Hydrographic Service and the Admiralty. However, for actual practical use at sea, these charts have severe limitations, which will be discussed later (Chapter 6).

1.2.2 Evolution of Weather Routeing

Over the last twenty years a new awareness of the benefits to be gained by resurrecting many of the techniques practised formerly has arisen. This has been facilitated by:

(1) The introduction of new and sophisticated methods of communication, notably the facsimile recorder.

(2) Intense competition in the industrial world, necessitating development of more efficient methods of operation. More

stringent steps necessary in reducing consumption of high cost fuel oil.

(3) The advent of improved techniques in weather forecasting, notably in the fields of numerical analysis, the use of orbital weather satellites, and the electronic computer.

(4) Enormous advances have been made in recent years in the collection and analysis of oceanographical and meteorological data. (The use of deep sea responder buoys, transmitting to satellites, which store and retransmit to a central control).

(5) The development of organisations such as W.W.W. and W.M.O. has streamlined existing international co-operation.

These factors have made new developments possible. I have suggested that the mariner has neglected the "art" of studying his environment and its interfaces (for seventy years or so), because of his obsession with mechanisation. The science of meteorology meanwhile has been progressing steadily ashore and the seafarer is now in a position to make use of this. To do so, however, he must approach the subject in a scientific manner, using all technological aids now at his disposal.

In the early 1950's meteorologists working for commercial forecasting organisations in the United States pioneered a routeing service for shipping. This led to the introduction of Optimum Track Ship Routeing (O.T.S.R.) by the Naval Hydrographic Office of the U.S.A. in 1956, JAMES (*51*). At the outset this service was provided only to military supply ships and during this period techniques and operational procedures were evaluated. The service was considered satisfactory and O.T.S.R. was offered as a separate service to merchant ships in 1958. American military vessels and supply ships are routed by Military Sea Transport Service, now provided in the Atlantic by U.S. Fleet Weather Central Norfolk, and in the Pacific by U.S. Fleet Weather central Alameda and Guam. This latter is also used by some twenty per cent of American merchant marine ships while under government time charters with supplies and aid cargoes.

It is important to emphasise that weather services in the U.S. are a function of both government and private enterprise. It was the efforts of these earlier men of foresight which laid the foundation of the present network: Louis Allen on the east coast of the States and Howard Kastner on the west coast. Dr. R. James of the U.S. Naval Hydrographic Office was the main power behind governmental services. There are now seven private weather service corporations and weather consultants engaged in providing specialised forecasts to merchant ships. The leading company is Ocean Routes of California (*82*).

The Environmental Science Services Administration, Weather Bureau, U.S. Department of Commerce, are responsible for collecting, analysing and transmitting all meteorological data. The specialised private weather services are dependent, as in other countries, on the national corporation.

In 1960 the Netherlands Meteorological Institute initiated a service in close co-operation with the Holland-America Line, and it was decided at the outset that a joint specialisation was necessary, and that operators issuing recommendations and guidance should be fully acquainted with and have experience of procedures on board, in addition to the basic meteorological skills required.

The Bureau now routes the trans-Atlantic ships of Shell Tankers (U.K.) Limited, besides many Dutch vessels. (Currently in excess of 700 ships from some 20 companies are routed annually by the de Bilt Bureau) MOENS, W.D. (*71*).

Routeing recommendations for Atlantic shipping have similarly been issued by the Seewetteramt, Hamburg, originating at about the same time as the Dutch service. The Germans confined their activities initially to a few voyages to Canada on a trial basis. There was a marked increase in demand in 1966, since which time the service has steadily expanded, MAULE, A.G. (*67*).

The Japanese advise vessels in the Pacific,but the main centre for this Ocean was Pacific Weather Analysis of California, who made prodigious claims of the success of their service. This company became Ocean routes of California when a world wide service was made available during the 1970's.

The Russians have introduced advisory schemes and have recognized the benefits of weather routeing. Only limited information is available at present on these services.

In 1968 the Meteorological Office at Bracknell introduced its weather routeing service and is now one of the leading shore-based routeing establishments, MACKIE, G.V. (*65*).

There are two main methods of application of the basic principles of routeing:

(1) From the shore by:

(a) A government department.

(b) A shore-based consultancy firm.

(c) A shipping company employing specialist meteorological and nautical advisers. (Of little importance unless allied to (a) or (b).

(2) On board ship:
Via a facsimile receiving/recording device operated by a ship's navigating officer.

There are relative advantages and disadvantages to each method. These are analysed after discussion of the concept and mechanics of routeing (7.1.1). Thus, in the 1960's, routeing services were established, but prior to this mariners had depended on seasonal mean tracks and followed time honoured climatological routes. Many ship masters still adhere to this practice.

Little documentation exists on the practice of weather routeing as conducted from on board ship. However, the author is fortunate in having had personal experience of weather routeing ships that he has served on as Master or Chief Officer as well as a considerable correspondence with many ship masters who have been trained by him at Plymouth. Most of this correspondence relates to actual case studies of particular routeing examples and has provided a source of regular data for study over the last ten years or so.

1.2.3 Climatological Routeing

Taking into account seasonal fluctuations, especially applicable in middle latitudes, routes are advised usually on a winter or summer basis. These historical routes are based on a voluminous amount of past data and, if average conditions prevailed throughout a voyage, a seasonal track based on climatology would be adequate. However, average conditions seldom if ever occur over a large part of an ocean for several consecutive days.

Monthly pilot charts are provided with wind and current roses giving preferred velocity and direction of mean wind and current, superimposed with advised routes between main terminal ports. Such charts are published by the Admiralty and U.S. Hydrographic Office, and, as a mean seasonal guide, are excellent. In the absence of additional information they are an improvement on an habitual adherence to the great circle track, but have severe limitations.

The standard shipping lanes contained in the handbook "OCEAN PASSAGES FOR THE WORLD" (*3*), were originally based, for the North Atlantic, on:

(1) The southern extension of Arctic ice.

(2) A mean position of the appropriate oceanic high pressure systems.

(3) Pre-supposing that the majority of depressions would tend to track polarwards of these systems.

(4) Favourable currents.

It can be illustrated that middle latitude depressions and, hence, extremes of wind and waves in these zones, fail to adhere to simple rules of thumb. The deviation of storm centres from the predicted monthly mean track, is so large as to make this alone as a means for routeing ships completely inadequate.

However, climatological generalisations may be made with some conviction. It is a fact that a major cell of severe sea wave activity is centred between latitudes 50^{o}-60^{o}N in winter with extensions of intense seas protruding into the Denmark Straits and Norwegian Sea and along the south east coast of North America. Annual maxima of frequency of severe seas in these regions of the North Atlantic Ocean (because of the many cyclones that traverse them during this season) present the most hazardous wave conditions for ship operations and induce a high proportion of ship speed reductions. Again, it is a fact that a higher proportion of ship speed reductions will occur at lower latitudes during winter than during the remaining seasons because of the more southerly trajectories of the majority of these migratory storms. The mean monthly storm path in January is equatorwards of the mean monthly summer path.

Annual minima of frequencies of high seas make summer the season of most favourable wave conditions punctuated by the lower latitude tropical revolving storms, some of which track polarwards, becoming extra-tropical depressions and retaining much of their intensity. The mean annual path of tropical revolving storms gives a clearer indication of predicted position than middle latitude data, but it is still subject to wide deviations.

An average of only seven hurricanes a year are normally experienced in the North Atlantic, with about four times this number in the North Pacific Ocean, (*73*). Mariners are well versed in the ways of a tropical storm, its localised severity and dangers in the mature stage. However, as the fetch in such a storm is limited, often the waves are not fully developed and are no bigger than waves related to an extra-tropical depression. The tropical storm is transient whereas a mature depression can be stationary for a few days with wind changes at fronts promoting an added danger.

The "Law of Storms" is mainly concerned with the close quarters situation, that is when the vessel is in the vicinity of the storm. Weather routeing attempts to avoid storms, certainly when a strategic route is followed, although this may not necessarily be the case for the optimum track procedure. It is therefore necessary that the initial formation and subsequent movement of the tropical revolving storm is followed by the forecasting services. Observation by weather satellites has facilitated this, and a greater forecasting accuracy has resulted. The normal surface analysis on the facsimile networks incorporates this information.

Thus, although charted information gives the navigator an indication of the likelihood of bad weather, it gives no detail of persistence or duration, and indeed may dissuade him from taking advantage of what may be the best available passage at that time.

It should be recognised that this system of "climatological routeing" has been particularly valuable in those areas of the world such as the Indian Ocean and China Sea, where a regular monsoon cycle predominates and in other areas, mainly tropical, where weather and wave conditions are in a settled state for long periods of time.

However, as has been stated, only limited success is possible in the North Atlantic from a purely climatological approach because of the large departures in the diurnal pressure distributions from the seasonal normals.

2. SEA WAVES

2.1 Wave Form and Characteristics
- 2.1.1 Results of Classical Theory
- 2.1.2 Practical Wave Observation by the Mariner

2.2 Aspects of Modern Wave Theory
- 2.2.1 Turbulence Theory Applied to Waves
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2.3 Wave Forecasting
- 2.3.1 Wave height (Dependent Variables)
- 2.3.2 Wave height formulae

2. SEA WAVES

2.1 Wave Form and Characteristics

2.1.1 Results of Classical Theory

Classical wave theory was developed in the late eighteenth and early nineteenth centuries by Laplace, Gerstner and Stokes. (*96*). Solutions of the wave equation were obtained subject to several simplifying assumptions. The results state that the motions of particles in waves are trochoidal; particles at the crest move in the direction of wave advance, and in the trough an opposite motion prevails. For waves in the deep sea (i.e. the depth of the sea exceeds half of their wavelength), the wavelength L, wave celerity C and wave period T are related by the classical formula

$$C^2 = \frac{gL}{2\pi} \qquad \text{... 2(i)}$$

The general relationship Lf = C, enables the wave period to be evolved,

$$L = \frac{2\pi C^2}{g} = \frac{gT^2}{2\pi} \qquad \text{... 2(ii)}$$

and

$$T = \left(\frac{2\pi L}{g}\right)^{\frac{1}{2}} = \frac{2\pi C}{g} \qquad \text{... 2(iii)}$$

are derived. The waves have an amplitude which is small relative to their length.

With the notable exceptions of Vaughan Cornish at the beginning of the twentieth century, very few observations were made of real waves in the ocean until World War II, when they were required for invasion plans. The appearance of waves in the open sea is often that of a confused surface, with waves of varying dimensions over a wide spectrum of wavelengths. Nevertheless it is usually possible to apply the terms : celerity, period, wavelength and height, and even to estimate their values without the use of wave recorders, (see below, 2.1.2) as generally waves of a particular frequency dominate and are hence observable.

Observations tend to agree with the results of classical theory; waves in the open sea typically have amplitudes which are small relative to their length, and often exhibit a trochoidal shape.

Many measurements have been made at sea in order to establish the validity of the numerical relationships stated, and observed values are in reasonable agreement with the theoretical expectation. e.g. After KRÜMMEL (*59*) for Trade wind region of the Atlantic:

<u>Table 2.1.</u> <u>Comparison of observed of observed and computed wave parameters</u>

Observed	Computed (1)	Computed (2)
wave velocity (ms^{-1}) 11.2	$\left(\frac{gL}{2\pi}\right)^{\frac{1}{2}}$ 10.8	$\frac{gT}{2\pi}$ 10.5
wave length (m) 65.0	$\frac{2\pi C^2}{g}$ 70.0	$\frac{gT^2}{2\pi}$ 61.0
wave period (sec) 5.8	$\left(\frac{2\pi L}{g}\right)^{\frac{1}{2}}$ 6.0	$\frac{2\pi C}{g}$ 6.2

These results are typical of comparisons made by other researchers.

Classical theory gives little information on wave height. In general the observation of wave height is considered more accurate than that of wave length, nevertheless it is a subjective art fraught with attendant inaccuracies varying widely with the knowledge and experience of the observer.

2.1.2 Practical Wave Observation by the Mariner

The mariner intimately involved with the sea should be aware of the difficulties involved in predicting wave height and of the complexities of the relationship between wind and waves, an essential factor in the weather routeing concept.

A greater theoretical knowledge will provide an awareness of the limitations of wave prediction. A mariner will then be in a better position to up-date a forecaster's work and gain the maximum advantage from wave forecasts.

He may also modify forecasts to agree with the swell experienced on station.

To quote NEUMANN and PIERSON (87),"Some methods will provide useful results for typical situations, especially if used by a person who is experienced in the procedure and is aware of its inadequacies".

The seafarer with his experience in observation is also able to make a contribution in providing accurate records for the analyst, to be used as a comparison by marine scientists and oceanographers in their theoretical approach to the problem.

As ship performance curves are often constructed from log book and log abstract information, care and attention should be taken with all observation and recording of sea data.

Instructions to observers, EVANS (*31*), state that if the length of the waves is short in comparison with the ship's length, the observer should take up a position as low down in the ship as possible, preferably amidships, where the effect of pitching is least and on the side of the ship from which the waves are advancing. The height (H) is then estimated from the appearance of the waves on the side of the ship, at times when the rolling and pitching are least.

If the length of the waves exceeds the length of the ship, the observer is told to take up a position so that his eye is in line with the advancing wave crest and the horizon, when the ship is vertical in the trough. The height of his eye above the ship's waterline is then the height of the wave.

The best measurement of wavelength (L) and period (T) is made with the ship's head or stern towards the wave direction. The time (t) taken for a crest to travel between the bow and stern of the vessel is noted, hence yielding the velocity (C) of the wave.

$$C = \frac{L_s}{t} \mp V_s \qquad \text{... 2(iv)}$$

where L_s is length of waterline,
and V_s is speed of the ship.

The period T can be found by noting the time interval Δt for successive wave crests to pass.

$$T = \frac{C\Delta t \pm V_s \Delta t}{C} \qquad \ldots 2(v)$$

the wavelength is the product of these two formulae.

It should be noted that, in general, when readings have been taken using wave recorders, scientists have found almost exact agreement with the observations of seasoned mariners, DRAPER (*23*) "A man who has spent a lifetime on the sea invariably develops a keen sense of observation which in this case can be used to his own advantage."

To give an example of the extremes of wave heights observed:- in October 1970 in the Norwegian sea, measurements were taken from an oil rig in a gale when 22m high waves were observed. Ships in the vicinity reported similar values. The highest wave observed is usually attributed to the American ship RAMAPO, of almost 34 metres. However, these are isolated values and in excess of the corresponding significant wave height. The existence of such waves does serve to indicate the necessity for a vessel to reduce speed in good time should she be slamming, as apart from vibrational stresses, the possibility of freak waves occurring causing heavy structural damage is always likely.

2.2 Aspects of Modern Wave Theory

2.2.1 Turbulence theory applied to waves

Assumptions have to be made when applying theory and mathematical formulae to wave generation. The initial assumption is of an ideal steady state wind field with the properties of the resulting wave motions assumed to be in a similar steady state.

Interactions at the air-sea interface are complicated. Mathematical models exploring these interactions are necessarily complex and as yet incomplete, SHEPHERD (*94*).

Sea waves are generated when the frictional drag of the wind on the sea surface creates ripples. As the wind strengthens the side of each ripple presents a surface against which the moving air can press directly. Because winds are by nature turbulent and gusty, wavelets of all sizes are at first created. The small steep ones break, releasing some of their energy to turbulence and possibly contributing part of it to larger waves that overtake them, so waves will not be regular as dispersion of particles of varying velocities pass into adjacent waves.

Air movement over such a surface is described by turbulence theory as motion over an "aerodynamically rough surface". As eddying wakes form behind the surface corrugations, which are the small sea waves, pressure differences build up between upwind and downwind sides of the roughness elements and viscous drag becomes negligible.

A surface which may be smooth at one air speed, may become rough at a higher speed as the viscous limit expressed by the Reynolds number, in its general form : (velocity multiplied by length divided by viscosity)

$$R_e = \frac{Vl}{\kappa} \qquad \text{... 2(vi)}$$

is overcome. A surface can be considered aerodynamically rough if the Reynolds number exceeds 5. Hence the derived relationship SHEPHERD (*94*)

$$R_e = \frac{u_* Z_o}{\kappa} > 5 \qquad \ldots 2(vii)$$

u_* is the frictional velocity

Z_o is the roughness element of length

κ is the kinematic viscosity

When the velocity increases to exceed this limit a pressure build-up will occur. Pressure will be greater on the windward slopes of waves than on the slopes sheltered by the crests. This condition will only prevail as long as the waves travel at a velocity (C) less than the wind speed (V). In practice smaller waves travel faster than larger waves, so the velocity C will relate to some mid point of the size range.

JEFFREYS (*94*), in the first serious attempt to investigate energy in sea waves, found that waves grow only if

$$C\ (V - C)^2 \geqslant \frac{4\kappa g\ (\rho - \rho^1)}{S\ \rho^1} \qquad \ldots 2(viii)$$

κ is kinematic viscosity of water

ρ is density of water, ρ^1 density of air

S is a non-dimensional sheltering coefficient

In appealing to observation, it was found that at wind velocities of about one ms^{-1} distinct waves appeared; the corresponding value of 'S' the sheltering coefficient was 0.27. Classical turbulence theory gives a value of

u_* as $30cms^{-1}$ for one metre wave heights.

Drag produces roughness which in turn produces drag until a theoretical equilibrium level is attained for a constant wind velocity, where $(C_D)_Z$ is a drag coefficient

$$\left(\frac{u_*}{u_Z}\right)^2 = (C_D)_Z$$

The corresponding roughness element (Z_0) for the sea is given by

$$Z_o = \frac{1}{50} \quad \frac{u_*^2}{g} \qquad \text{... 2(ix)}$$

(a factor of $\frac{1}{50}$ is used as a generalisation this can vary from $\frac{1}{10}$ to $\frac{1}{100}$ in practice)

If this is applied to the Reynolds number equation 2(vii) the limit is just achieved for one-metre waves.

A wind velocity of one metre per second is usually associated with wave heights considerably less than one metre but a broad agreement is achieved here between classical theory and observation.

Because of the irregularity of wave trains a term "significant wave height" is now used. This refers to the mean height of the highest one third of the waves experienced.

Unless otherwise stated all future reference to wave heights will pre-suppose this definition.

It should be noted that the high value of the sheltering coefficient

($S \simeq 0.3$) deduced by Jeffreys was not substantiated by pressure measurements carried out over solid models of wavy surfaces which indicated S values of the order of 0.05 suggesting that the pressure forces produced were much too small for Jeffreys' mechanism to be effective. It is only recently that respectable measurements of air flow over waves have been obtained (BANNER and MELVILLE, (*8*)), and evidence for flow separation over breaking waves has been found. It is now clear that Jeffreys' original hypothesis has limited application as in a fully developed sea there are many breaking waves, indeed the high frequency part of the spectrum (ω^{-5} region) is dominated by wave-breaking. (see Section 2.2.2)

Once waves have appeared on the sea surface, their presence modifies the air flow. These perturbations of the original mean shear flow may be analysed through linear stability theory in its simplest form, SHEPHERD (*94*).

It must be noted in this work, as it is intended to be of use to the practical mariner, that all of the aforementioned turbulence wind-wave generation theories assume that air flow over the sea is two-dimensional. All sailors who have observed the sea surface over many sea-watches will know this to be a gross idealisation of the actual wind field.

2.2.2 Spectral representation

The most complete mathematical description of a sea surface is obtained in terms of spectral representation. A wave spectrum is the envelope of an aggregation of spectral bands, each of which represents the energy contribution from a single component, periodic wave train. This theory is developed in terms of ship responses in Chapter 3, making such an approach entirely compatible in this chapter. Data is collected either from a stabilised single wave-buoy, where vertical measurements obtain, or from a set of three connected buoys. The former system gives a point spectrum which, when used with a spreading function accounts for direction as well as the "short crestedness" property of a sea. The latter system enables measurements to be taken in more than one plane.

A more complete description of real sea state may be represented by a two-dimensional spectrum, which indicates the directional property as well as the amplitude frequency relationships. Since the area under the one-dimensional spectrum is a measure of the average power of the sea state, then the volume under the two-dimensional spectrum must also measure the average power and angular integration of such a spectrum must produce the fixed point spectrum. Two-dimensional spectra are very difficult to obtain in practice, but those that have been measured tend to support the hypothesis that a directional spectrum can be considered the product of two independent functions.

As far as operational requirements are concerned the main contribution to the mariner for weather routeing his ship is that the description of the sea by means of a wave spectrum may be translated into certain statistical parameters such as significant wave height and mean period (ROBERTSSON (*90*)). This is based on the assumption that the irregular wave pattern that makes up the sea surface consists of an infinitely large number of sinusoidal waves superimposed on each other, each component having its own frequency, amplitude and phase. The surface elevation at one point as a function of time S(t) may then be expressed as:-

$$S(t) = \sum_{i=1}^{N} a_i \cos(\omega_i t + \alpha_i) \qquad \ldots 2(x)$$

where a_i = amplitude for component wave with frequency ω_i

α_i = phase displacement " " " " ω_i

N defines the limit of summation referring to a finite number of observations

assuming α_i to be evenly distributed over the interval $0, 2\pi$.

The mean value of each component = 0 and

The variance = $\frac{1}{2} a_i^2$.

The energy of a single gravitational wave is obtained by :-

$$E = \tfrac{1}{2} a^2 \rho_g b \lambda \qquad \ldots 2(xi)$$

where a = wave amplitude

b = breadth of wave

λ = wave length

ρ_g = weight of unit volume of water.

Spectrum analysis is used to evaluate the energy from a family of waves and an energy spectrum may be used to represent a wave system assuming that the period of time of representation is short enough to regard the wave surface as a stationary ergodic random process (usually accepted to be in the order of 20-30 minutes).

Because of variables such as wind speed, duration of blow and fetch, the wave spectra representing a sea will vary in time and space.

For the description of the sea surface often a modified PIERSON-MOSKOWITZ (*88*), wave spectrum is used as an approximation of the frequency distribution of the energy :

$$\frac{S\zeta(\omega)}{\bar{H}^2_{1/3}} = \frac{\alpha}{\omega^5} \exp\left(\frac{-4\alpha}{\omega^4}\right) \; ; \; \alpha = \frac{124}{\bar{T}^4_2} \qquad \ldots \; 2(xii)$$

where $S\zeta(\omega)$ is the wave spectral ordinate value at frequency ω,

with the spectral moments:

$$m_n = \int_0^\infty S\zeta(\omega) \,.\, \omega^n \,.\, d\omega.$$

where

ω = circular wave frequency

significant wave height $\bar{H}^2_{1/3} = 4 \cdot \sqrt{m_0}$

average zero-crossing wave period $\bar{T}_2 = 2\pi \sqrt{m_0/m^2}$

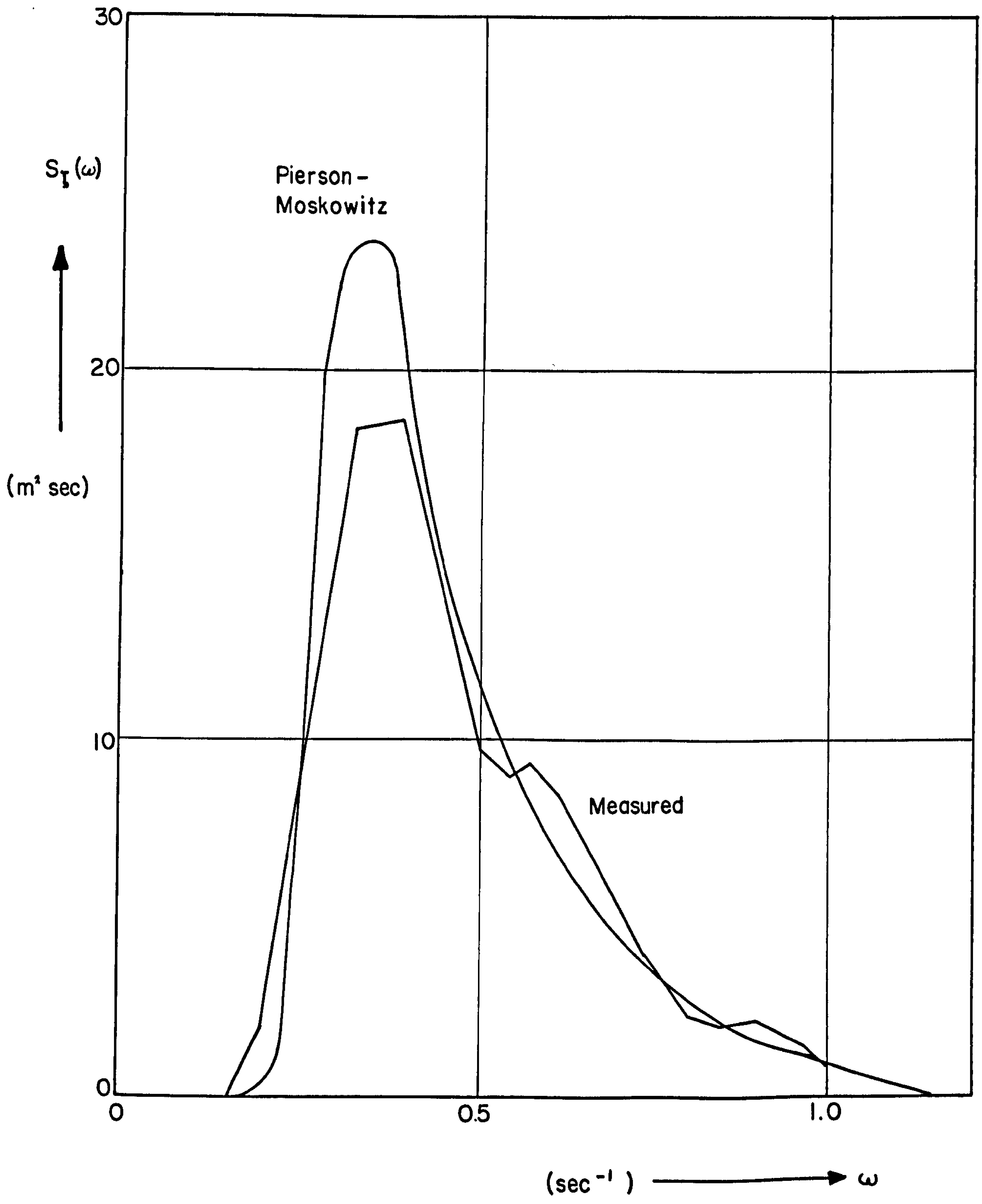


FIG. 2.1 Comparison between a measured and a Pierson-Moskowitz wave spectrum.

So the spectral values vary with the squared significant wave height. In reality the spectral form differs from this formula and gives only a mean distribution. Fig. 2.1 shows a comparison between a measured wave spectrum during a storm in the Atlantic Ocean on 4th February 1979. Another important factor is the distribution of the wave energy over all directions. Often a cosine-squared spreading will be used :

$$S\zeta_{(\omega,\mu)} = \left\{ \frac{2}{\pi} \cos^2 (\mu - \bar{\mu}) \right\} . S\zeta(\omega) \qquad \ldots 2(\text{xiii})$$

with :

$$- \pi/2 \leqslant \mu - \bar{\mu} \leqslant \pi/2$$

where $\bar{\mu}$ is the dominant wave direction. It has been assumed here that for each direction the shape of the energy distribution over the frequency range is the same. In reality this distribution depends on the instantàneous local weather situation (sea) and the weather in the whole ocean in the recent past (swell). So deviations of these distributions will certainly appear as for instance when sea and swell come from different directions.

The recognition of an observed peak in the wind-wave spectrum suggesting that an interactive process is at work, which effectively transfers energy from short to long waves and further complicates proceedings. The wave terms calculated for the JONSWAP spectra LE BLAND and MYSAK (62), strongly indicate that nonlinear interactions within the wave spectrum are responsible for the presence of a sharp peak in the wind-wave spectrum. It should be noted that these spectra were devised for the North Sea and are not necessarily descriptive of the open ocean condition.

Wave spectrum $\Delta t^2 \; (\omega \theta_{ss})$

Location 47° N 41° W

Time 22 Oct. 1969 1200Z

Wind speed 30 Knots

Wind direction 98 Deg

$c_w^2 = \Sigma_\theta \Sigma_w \Delta t^2 = 19{\cdot}09 \text{ ft}^2$

$\sigma_w = 4{\cdot}37 \text{ ft}$

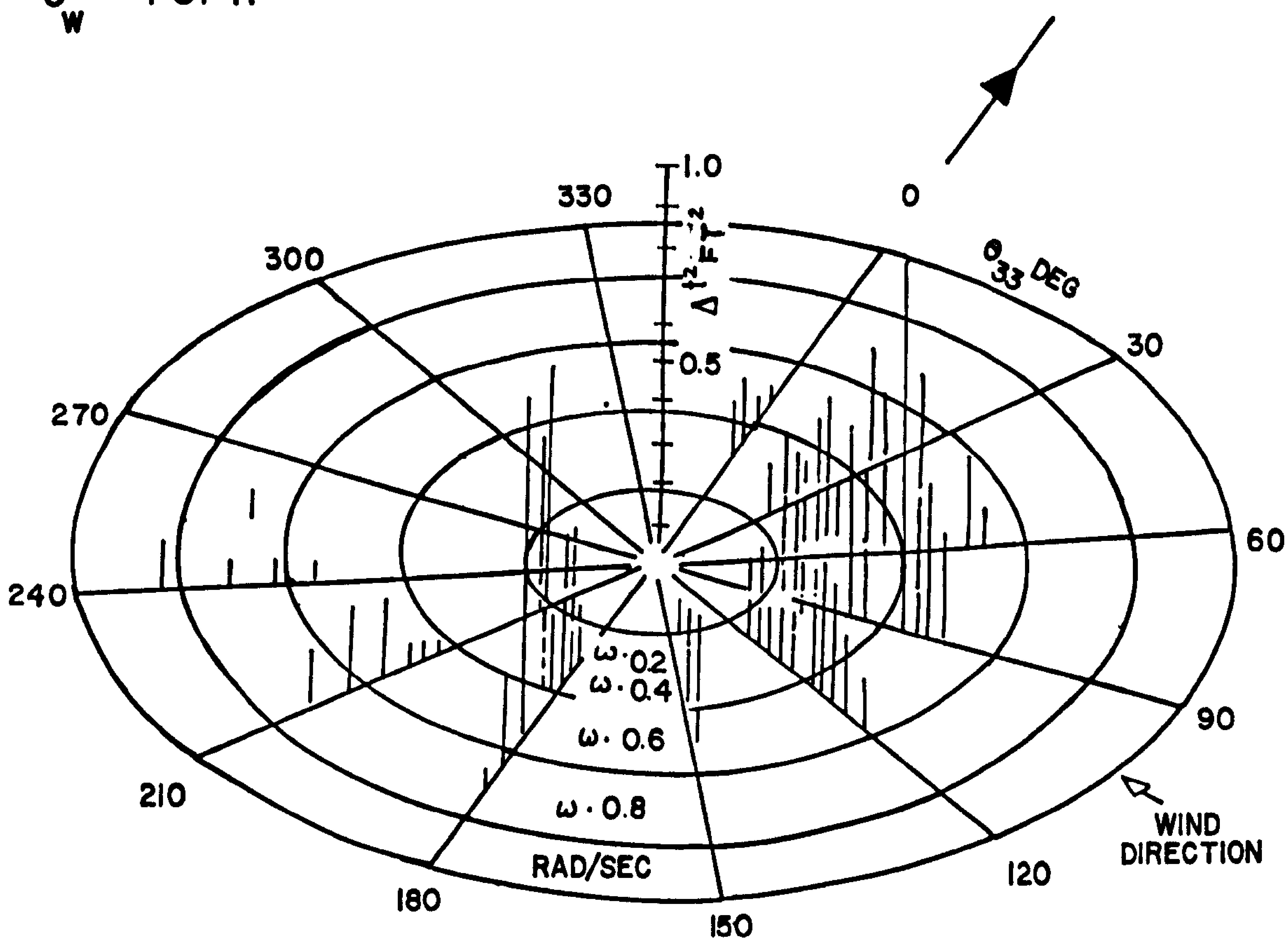


Figure 2·2 Typical Directional Spectra by Directions and Frequencies

The United States Navy has developed a spectral ocean wave model, based on directional spectra obtained from wave rider buoys, intended to forecast for up to 72 hours, see Fig. 2.2.

I am sceptical concerning the applications of such models by ships' officers to a weather routeing exercise. I consider the general form equations, which result from an analysis of several spectra, to be more applicable from a general operational standpoint.

CARTWRIGHT (*20*), has recognised the complexity of ocean wave spectral analysis; "Understanding of the mechanisms of wave generation by wind has made great progress since the total inadequacy of some 20 years ago, but the mechanisms are now seen to be so complex that realistic wave forecasting can only be attempted on national funding".

2.3 Wave forecasting

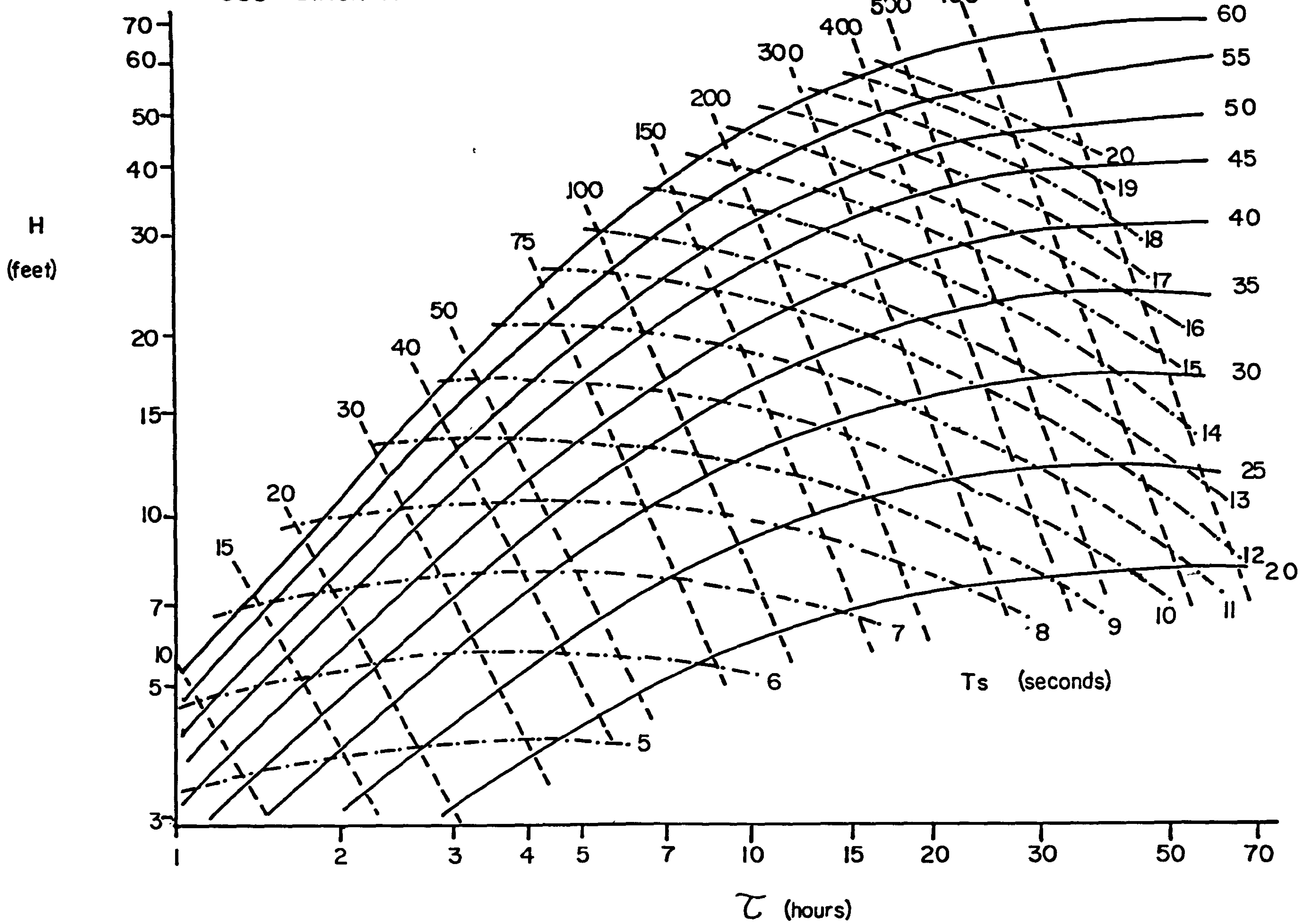
2.3.1 Wave height (dependent variables)

The weather routeing exercise presupposes the use of a set of ship performance curves or some ship response data using ship speed as a dependent variable against the argument of wave height as discussed in Chapter 3.

Of all the sea state dimensions discussed the mariner is interested particularly in wave height. It follows that we should therefore consider the dependent variables affecting wave height. These are generally considered to be: Wind speed ($\underset{\sim}{V}$), fetch (F), and duration of blow (T). Other considerations may be sea temperature, swell factors and/or calculated constants

Fig. 2.3

CSS DIAGRAM



incorporating one or more of these variables generalised for a particular ocean area.

Figure 2.3 shows a cumulative sea state (C.S.S.) diagram incorporating the variables of wind velocity (U kts), fetch (F, nm), and Duration of blow (T hrs) to arrive at the wave height (H ft).

2.3.2 Wave height formulae

Wave theory has been developed on both sides of the Atlantic by physicists, oceanographers, meteorologists, naval architects and scientists in general and consequently various systems of units have been used. Thus wave charts are broadcast from America incorporating the traditional system with wave heights in feet, whilst European networks give them in metres; no standardisation exists. Therefore the mariner will encounter both feet and metres. No attempt has been made to standardise here, and all formulae and theory appear in their original form.

Comparison is achieved in Fig. 2.4 by using scales for both sets of units.

Many computed formulae exist using the various parameters in 2.3.1. As the weather routeing principle involves the use of wave height charts it is important that a brief synopsis and evaluation of some of these formulae is undertaken.

The earlier researchers, Zimmerman, Cornish and Rossby, for example, arrived at their wind/wave relationships by empirical means. Observations were adjusted by the basic relationship formulae, 2(i) - (iii) and curves were fitted to the results.

The empirical formulae so derived have distinct limitations and can only be considered to apply to the area where the observations were taken.

Examples:

Cornish	$H = 0.48V$	... 2(xiv)
Zimmerman	$L = 10.62H^{4/3} = 3.55V^{4/3}$	... 2(xv)
adjustment gave:	$H = 0.44V$	... 2(xvi)
Scripps Institute	$H = 0.026V^2$	... 2(xvii)
Rossby	$H = \frac{0.3}{g} V^2 = 0.0305V^2$	... 2(xviii)

(Equations 2(xiv) - (xviii) in S.I. units)

In 1943 SVERDRUP and MUNK (*96*), introduced a wave prediction method, composed after an assignment from the U.S. Navy Hydrographic Office. They adopted similar techniques to Jeffrey's using a sheltering coefficient and computed the average rate at which energy is transmitted from wind to waves by normal pressure and tangential stress. Duration and fetch factors were included in these energy equations.

M. DARBYSHIRE (*22*), in 1952 stressed the importance of fetch and duration in her research, factors which are fundamental to the profile of an ocean wave (Fig. 2.5). She showed that the wave pattern is almost fully developed after a fetch of two to three hundred miles.

With the mathematical tools of statistics, probability and sampling, CARTWRIGHT and DRAPER (*20*), have had a measure of success in the 'sixties. Latterly NEUMANN and PIERSON (*87*), have attempted to quantify wave properties using power spectrum analysis. Reasonable relationships to observations at sea have been made by these methods.

The theory can be further extended to illustrate how sea waves can display the phenomena of beat frequencies, standing waves and modulation.

Table 2.2 for Fig. 2.4

Origin	Formula	Equation No.
Zimmerman	$H = 0.44v$	2(xvi)
Cornish	$H = 0.48V$	2(xiv)
Rossby	$H = 0.3V^2/g$	2(xviii)
Scripps	$H = 0.26V^2$	2(xvii)
Pierson & Moskowitz	$H = 0.0185V^2$	2(xxi)
Scott (1)	$H = .075 (1-\exp(-0.047F))V^{3/2}$	2(xxii)
Scott (2)	$H = .075V^{3/2} + H_S$	2(xxiii)
Darbyshire	for 24 hrs duration	Fig.2.5

Pierson then related the energy (E) of the spectrum so obtained to the wave frequency (K) and then to the wave height.

$$H = \left(\frac{E}{K}\right)^{\frac{1}{2}} \qquad \ldots 2(xix)$$

The lack of functional relationships between wind and sea states is usually associated with their non-constancy in time and partly attributed to swell intrusions from other systems. However, in the ideal case of a steady wind blowing for a sufficiently long time and with a large fetch (the fully developed wind/sea spectrum), PIERSON and MOSKOWITZ (*88*), used some fifty spectra from the Atlantic to arrive at an energy density formula, derived from equation 2(xii)

$$S\zeta(\omega) = \frac{8.39}{\omega^5} \exp\left(-\frac{9.76 \times 10^4}{\omega^4 V^4}\right) ft^2 sec \quad \ldots 2(xx)$$

Spectral density is inversely proportional to the fifth power of the circular wave frequency "ω". This yields the more manageable

$$H = 0.0185\ V^2 \qquad \ldots 2(xxi)$$

where V is wind speed in knots and H is wave height in feet.

Earlier data was collected by direct visual observation; recent studies use mechanical wave recorders. Darbyshire used pressure capsules on the sea bed to record wave passage and height (limited to shallow water). Later wave recorders were more sophisticated. TUCKER (*102*), used an instrument which varied its capacitance between the length of the vertical wire leading into the water from the head, the wire acting as the di-electric. This capacitor forms part of a tuned oscillator circuit, which after appropriate rectification and amplification is recorded.

Such instruments were installed on certain lightships and ocean weather ships and other convenient observation posts. Now wave data collection is commonplace from the "wave-rider" buoys previously mentioned. Research is now being undertaken with remote sensing of wave heights using orbiting satellites, JOURNEE (*53*).

In 1968 J. SCOTT (*91*), as a result of a hydrodynamic research programme for the Vickers shipbuilding group, presented a controversial paper at the Royal Institution of Naval Architects. Scott established a basic formula relating wave height to wind speed when he analysed the spectra of J. Darbyshire and the spectra of Moskowitz and grouped observations into sets in which the fetch varied little. His analysis showed that minimum residual scatter occurs when H (wave height in feet) is made proportional to $V^{3/2}$ at constant fetch (F), resulting in:

$$H = 0.075\ (1 - \exp\ (- 0.047F))V^{3/2} \qquad \ldots\ 2(\text{xxii})$$

for an Irish Sea sample of spectra. When this formula was related to observations a standard error of prediction of 1.7 ft. resulted. (Thus the actual error was less than this standard on eighty percent of occasions). The form :

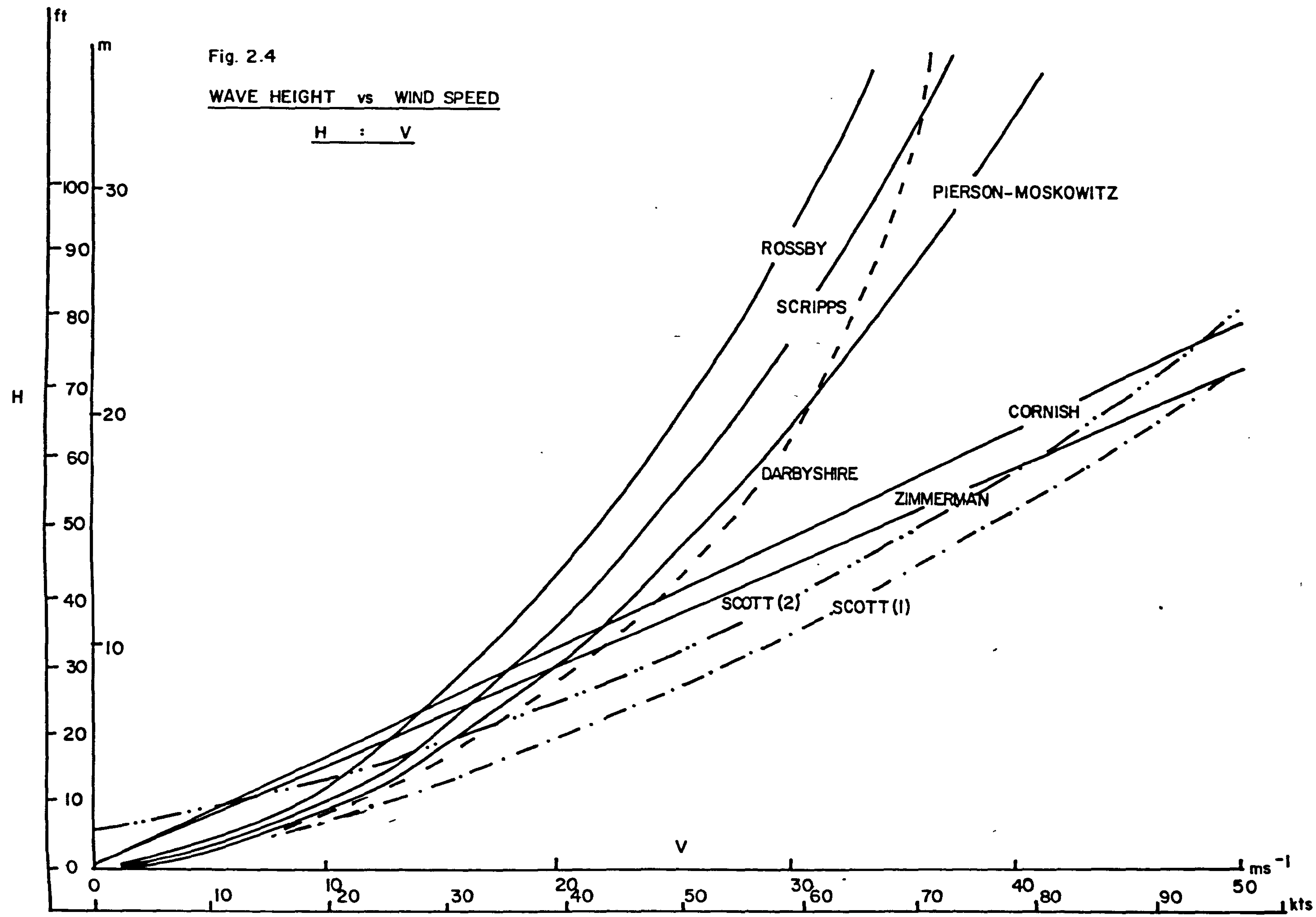
$$H = 0.075V^{3/2} + H_s \qquad \ldots\ 2(\text{xxiii})$$

was similarly prescribed for the open ocean as suitable for wave height prediction for wind speeds from fifteen to fifty-five

Fig. 2.4

WAVE HEIGHT vs WIND SPEED

H : V

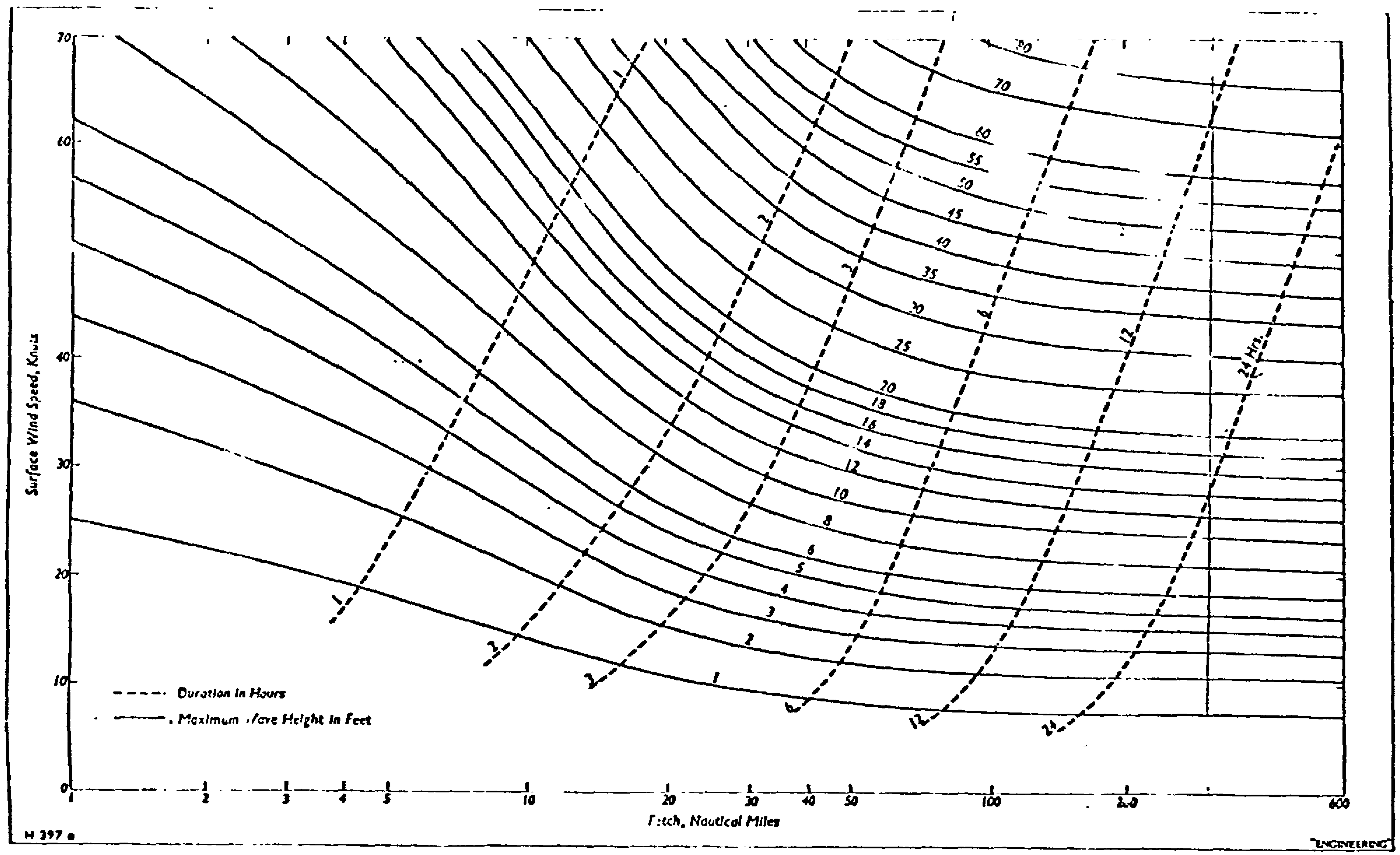


knots, where H_S is a swell factor with a mean value of five feet. This is the formula at present used by Bracknell in producing their wave charts.

The American services rely on the wave spectrum methods of PIERSON and NEUMANN (*87*), and latterly PIERSON and MOSKOWITZ (*88*).

Hence a picture is presented of a mixture of empirical and theoretical formulae all attempting to predict wave profiles by various assumptions of constant wind speed, constant fetch, constant duration and using 'ideal' relationships. One of the latest parameters recognised as affecting wave height is temperature. A change in temperature gradient across the water/air interface where the air is colder than the sea would, for a constant wind velocity, create a greater wave height. Measurements suggest $1^{\circ}C$ change in gradient can result in a ten per cent change in wave height, LE BLAND and MYSAK (*62*).

The graph (Fig. 2.4) illustrates an agreement between the chosen formulae within ± 1½ metres wave heights for wind speeds up to some twenty metres per second. Beyond this value large discrepancies in the relationship arise. For example, at wind speeds of thirty metres per second, Pierson and Moskowitz and again Darbyshire predict a wave height of some nineteen metres. Scott for the same wind speed derives a wave height of eleven or twelve metres. It should be emphasised that the wave height in question refers to the 'significant wave height' and experience in observation suggests that Scott's ocean formula (eq. 2(xxiii)), is reasonably accurate for the range shown in the graph. It would therefore appear that the sophisticated methods of the aforementioned oceanographers give excessive values at high wind speeds.



AFTER DARBYSHIRE. Fig. 2.5 Graph relating wave height to wind speed and duration, and to fetch; for oceanic waters.

It is interesting to note the close agreement of Scott with the empirical relationships of the earlier observers Cornish and Zimmerman. Cornish particularly spent many years in collecting observations, notably in the Bay of Biscay where the prevailing westerlies will ensure an undisturbed fully developed wave pattern.

In conclusion, it is to be expected that the methods of Pierson, Moskowitz and Darbyshire lose some of their validity when an attempt is made to express their complex methods of analysis in one simple, general relationship. All the equations incorporating a V^2 factor rise rapidly in H values for wind speeds in excess of twenty metres per second or so. Scott has achieved an apparently accurate compromise by using $V^{3/2}$ as a basic relationship for his formulae.

High wind speeds will often be generated by a transient weather system moving rapidly through a sea area, preventing the build up of a fully developed sea state because of the relatively low duration of blow and change of wind direction; possibly explaining the discrepancy between observed wave heights and heights obtained by theoretical formulae at high wind speeds.

The wave charts transmitted from the Meteorological Office, Bracknell, (using eq. 2(xxiii)) are realistic and give wave heights within one metre of the observed pattern (as reported by ships' officers) assuming the surface analysis upon which they are based is accurate.

3. SHIP SPEED ANALYSIS

3.1 Resistance of Ships

3.1.1 Added Resistance due to Wind
3.1.2 Added Resistance due to Vertical Motion
3.1.3 Added Resistance due to Steering

3.2 Powering and Speed

3.2.1 Propulsion in Waves
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3.2.3 Ship Losses

3.3 Ship Performance

3.3.1 Data Collection
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3.3.3 Ship Performance Curves

3. SHIP SPEED ANALYSIS

3.1 Resistance of Ships

Having related in Chapter 2 the wind speed to the sea state, it is logical in this work to consider the behaviour of ships in seaways. The naval architect designs a vessel based on requirements of the trade and specifications of the purchaser. The weather router is then largely interested in the additional resistances that this vessel may experience resulting in loss of speed in waves. GERRITSMA (*38*), estimated for a particular merchant ship a 12% speed loss in a Beaufort 6 head sea on the North Atlantic. He estimated Beaufort 6 weather was exceeded for 45% of the time during summer and 70% in winter for the particular North Atlantic route in question.

Hull form and ship dimensions are usually selected on the basis of calm water performance, rather than for sustained sea speed. As the weather routeing exercise necessarily deals with forecasted positioning, it is vital to have some predicted indicator of vessel behaviour related to the weather prognosis. The fact that little attention has been given to this variability in the original design of most vessels, increases this requirement. Basically a surface which is "smooth" at one speed may become "rough" at a higher speed as the Reynolds number is increased. "Corrugations" arise in a ship at abrupt endings of hull form or at irregular changes in hull section. An excessive curvature of hull form will create such an effect, the eddies incorporating backward drag. It is to be expected that in a well designed ship the magnitude of eddying resistance will be small, and "form drag" will be negligible. The problem is further complicated

(a) when a ship makes leeway and the rudder is used, and
(b) when a ship oscillates and presents a "rougher" hydrodynamic form to the fluid. The relative forward motion of a ship through water will generate a wave system around the ship and in its wake. The energy possessed by the waves can only have been derived from the ship's hull so that the energy transferred may be regarded as a resistance. Alternatively this resistance may be regarded as the vector total of all the local pressures acting normally on the surface of the hull taken in the fore and aft direction.

The waves produced by the pressure systems mainly at the bow and stern are energized by the ship's engines. Increased ship speed is only attained by increasing power input which makes larger waves with only a slight increase in ship speed.

The magnitude of the system will increase then with speed and is dependent upon ship form. Observation shows two separate and distinct series of waves caused by forward motion,

1. at the bow,
2. at the stern.

Each of these series in turn consists of :

1. a series of diverging waves, the crests of which slope aft
2. a series of transverse waves, crests nearly perpendicular to the middle line of the ship

The widening of the ship at her entrance throws off on each side a local oblique wave varying as to speed of vessel and obtuseness of the wedge. A similar oblique form occurs at the stern. The main point of these diverging patterns is that they almost immediately become dissociated from the vessel, passing into distant water, producing no further effect on the resistance total.

The transverse waves become important as resistance producing agencies as the relative speed of the ship to the fluid is pushed to higher values. The length of the wave can be said to vary as the square of the speed of the ship.

As has been suggested, transverse waves are set up similarly astern of the vessel and interaction of the bow and stern transverse waves can affect resistance. When the crests of the bow wave series coincide with the crests of the stern wave series, the resistance is at a maximum, conversely when the crests of the former coincide with the trough of the latter resistance is at a minimum.

A ship will be designed so that her wave making properties at her service speeds will give a minimum wave making resistance, however, this can only be effective for still water and when the superimposed motion of the sea disturbs this harmony an increase in resistance results.

A brief summary of added resistances that a ship may experience in a seaway follows. This summary is by no means exhaustive and merely catalogues the present state of the art. A practical analysis of resultant vessel behaviour is undertaken for two vessels S.T. "GONDWANA" a very large crude carrier (V.L.C.C.) and M.V. "DART ATLANTIC" a container ship.

3.1.1 Added Resistance due to Wind

Added resistance due to wind can be estimated from wind tunnel model tests. For ships with high superstructures or deck cargo the wind resistance can be considerable. A method for estimating this resistance was published by ISHERWOOD (*50*), giving empirical formulae for the determination of the two horizontal components of the wind force and the wind-induced yawing moment on any merchant ship form for a wind from any direction. It is of interest to note that the highest wind resistance is found when the relative wind direction is approximately 30^{0} off the bow. This is readily understandable as the ship presents a broader aspect to the wind and sea.

During a weather routeing exercise navigational requirements lead us to consider speed "over the ground", therefore the current must be determined. Information on predominant seasonal currents is available in many forms but in the context of the present argument it is relevant to consider the effect of the two fluids at the interface.

In a head sea a vessel may experience a surface current induced by the wind, an additional resistance, in effect, to forward motion. (By the same token a negative resistance in following seas).

As this current is due to the existence of friction between air and water, the speed of the current will increase with the speed of the wind.

According to EKMAN (*96*), the current speed V_c is determined by:

$$V_c = \frac{A}{(\sin l)^{\frac{1}{2}}} \cdot V \qquad \ldots 3(i)$$

where A is a coefficient evaluated at 0.015

l is latitude

There will be a slight deviation to the right of the parent wind (45^0 in a deep sea) in the northern hemisphere.

For the purpose of estimating sea-going qualities of ships, the projection of the current speed against the wind direction is of primary interest.

Hence

$$V_c = \frac{0.015V}{(\sin l)^{\frac{1}{2}}} \qquad \ldots 3(ii)$$

for lat 50^0 - 70^0 gives approximate values of the speed of the surface current induced by the wind (in the direction of the wind).

Table 3.1

mean wind speed

vs.

speed of current

Mean wind speed V m/s	12	18	25	29 <
Speed of current V_c in kts	0.25	0.40	0.55	0.65

An allowance of approximately half a knot reduction in moderate to heavy head seas can thus be attributed to this interaction at the interface.

Work by AMFILOKHIEV and CANN (*5*), suggests a measure of interaction between viscous and wave making properties of a ship. This has been established in fact for a "smooth" model but has not been evaluated for a "rough" model, and present research has yet to establish an effective relationship for a ship.

The passage of a wave train past a ship will produce a periodic change in the immersed shape of the ship and oscillation must result, changing the relative underwater hull form and increasing eddy making resistance, possibly increasing skin friction resistance hence reducing speeds.

3.1.2 Added resistance due to vertical motions

In an earlier work (*77*), I included a chapter on ship oscillations from first principles to recommendations on general ship operations in heavy weather with particular reference to slamming and predicting recommended operating limits. It is well known that the relative motions of a ship with respect to a water surface cause an added resistance to forward motion.

In 1972 GERRITSMA (*38*), published a paper based on the relationship between radiated energy of the damping waves and the added resistance. A close agreement was derived between theory and his experiments on ships in head to beam regular waves. In quartering and following waves the agreement is less spectacular, probably as a result of inaccurate values for added mass and damping at low frequencies. The calculations are based on an assumed linearity of ship response. The added resistance R_{AW} in a sea is said to vary with the square of the wave amplitude. The calculation in irregular waves is based on the superimposing principle for the components of the wave motion and resistance spectra. This leads to the following formula for the calculation of the mean added resistance in a given wave spectrum:

$$\bar{R}_{AW} = 2 \int_{0}^{\infty} \frac{R_{AW}}{\zeta_a^2} \cdot S\zeta(\omega).d\omega \qquad \ldots 3(iii)$$

where ζ_a = regular wave amplitude

$S\zeta(\omega)$ = wave spectral value

ω = circular wave frequency or frequency of wave encounter

The added resistance response operator $\frac{R_{AW}}{\zeta_a^2}$ may be obtained from model experiments or by calculation.

In using the theory of spectrum analysis the sea surface (as explained in Chapter 2) is assumed to be the result of the superimposing of many simple harmonic waves, each with its own characteristics of amplitude, frequency and celerity. Over a large range of waves the ship is regarded as a linear system with respect to its motions in regular waves. Thus when the wave height is doubled at the same ship speed, course and wave length, the resultant motion amplitude will also be doubled. The frequency response functions of a ship in regular waves, non-dimensionalised by the wave amplitude, provide the basis for calculations of ship motions in irregular waves using one of several techniques. Basically it is sufficient in this work to realise that there exists a compatability between the methods of spectrum analysis as applied to the sea state and the ship behaviour.

In 1953 the oceanographer W.T. PIERSON, and a naval architect M. ST. DENIS (*86*), presented a paper in which they stated: "the sum of the responses of a ship to a number of simple sine waves is equal to the response of the ship to the sum of the waves".

A method was then outlined whereby ships' behaviour in, and response to, irregular waves could be calculated, ROBERTSSON (*90*). The concept was commonly accepted and is now a standard procedure.

3.1.3 Added resistance due to steering

In a seaway, a vessel's heading will be disturbed by wind and waves. To counteract leeway rudder force is used. To quote an example after JOURNEE and MEIJERS (*53*): a beam wind of 9 on the Beaufort scale will need rudder angles of 15^{o} or more to maintain course. This is, of course, very variable depending upon several factors such as vessel design, forward speed, rudder efficiency etc. In waves, a ship will sail with yaw motions caused by the sea and the time delayed correcting effect of the rudder resulting in an increase in the ship's resistance. The mean added resistance during such a harmonic yaw motion will be in the order of:

$$\bar{R}_{ST} = .0000312 \nabla L \ \dot{\psi}_a^2 \text{ Newtons} \qquad \ldots \ 3(iv)$$

where ∇ = volume of displacement in m^3

L = length of the ship in m

$\dot{\psi}_a$ = rate of turn amplitude in deg/min

In effect this means for a container vessel similar to the M.V. DART ATLANTIC, with rate of turn amplitudes of 30^{o}/min at the service speed in a following sea a resistance increase of 20% of the still water value may be experienced.

3.2 Powering and speed

3.2.1 Propulsion in waves

A propeller may be considered to be an energy-transformer, whereby engine speed is transformed into thrust from the speed of advance of the propeller relative to the mean velocity of the immersed fluid. At a constant engine output an equilibrium position should be reached between engine speed and ship speed as long as the torque required by the propeller is in equilibrium with the torque delivered by the engine and the thrust delivered by the propeller is in equilibrium with the total resistance of the ship in the self-propelled condition.

The propulsive efficiency in waves is influenced by the action of the waves and by the ship motions, which result from the seaway. Much of the efficiency decrease is due to increased loading of the propeller from the added wave and wind resistances. GERRITSMA (*38*), has estimated increased power requirements in waves from the sum resistances of these effects.

Occasionally on good weather routes and more often in bad weather, added resistance and corresponding decreased propulsive efficiency in waves are then the main causes for speed loss.

3.2.2 Voluntary speed reductions

Violent pitching and heaving in a ship can lead to vibration of the structure due to the oscillatory bending or twisting of the ship as a whole or over local portions, further exacerbated by shipping water on deck.

Such vibrations can become extreme when a vessel is slamming into a head sea as the fore foot crashes into the sea surface. Should the propeller also emerge this will set up further vibrations and lead to speed reduction.

The ship will vibrate as a whole or locally if any likely mode of vibration is in resonance with the excitation. A vessel has itself a natural period of vibration and many local modes of vibration built into it depending upon the structure; scantlings of beams, plates etc.

Large modern ships are necessarily built with high tensile steel for the required strength to weight ratio to combat the huge local stresses to which they will be subjected. For example, modern container ships would need to have a main deck thickness of about three inches to support the weight of deck containers and give adequate hull strengthening but the use of high tensile steel obviates this. However this material is susceptible to vibrational stresses. It has become necessary for instance for two hundred thousand tonnes vessels to reduce to six or seven knots from a service speed of 17 knots to preclude natural vibration periods as a result of heavy head seas.

The old idea, practised in low-powered ships, of the vessel reducing speed herself as the sea forces her back, is not applicable to higher powered, possibly lighter scantling ships.

Modern, fast, container ships, which run to an exacting schedule, need to maintain high speeds even in adverse weather conditions, yet if speed reductions are left too late, bottom damage will ensue. Dry docking for plate replacement will be even more expensive for these ships than most others which spend a smaller proportion of their lives at sea.

Work on the diagnosis of slamming with recommendations as to possible alleviation of this problem has been taking place at the ship division of the National Physical Laboratory; this includes trials on vessels at sea.

Initially there is a problem of detection of slamming, exacerbated in modern all-aft vessels. Opinions differ as to the extent to which slamming may be detected, appreciated and avoided by masters and officers, but it is certain that a lack of uniformity exists here. Ideally, judgment as to speed of the vessel in head sea conditions is a balance of losses due to increased cumulative damage against economic gains from marginal increases in terms of shorter passage times.

In practice, this quantity is hard to assess as it can be subject to violent statistical fluctuations. One heavy slam could completely upset all the theoretical economic equations.

As speed gains would have to be considerable to outweigh lasting structural damage it would appear prudent to choose a ship speed low enough to eliminate all risk of a serious slam.

Slamming is manifested as local increases of pressure reaching some hundreds of pounds per square inch. This will, each time, cause deflection of the plating locally, usually within the elastic range, but sometimes causing a permanent set. On these local stresses are superimposed the vibration stresses, excited by the hydrodynamic pressures; a two node vertical vibrating or whipping is evident. This has a well defined period (e.g. a little less than a second for a cargo ship of about ten thousand tonnes gross) and stresses the main longitudinal strength members alternately in hogging and sagging in addition to those stresses owing to static loads and wave bending.

If an impact occurs on the bottom plating then it is inevitable that the bow of the ship will suffer a sharp deceleration as it returns into the water. Decelerations of 2.5g and 3g have been measured by an accelerometer; thus bow decelerations offer a means of classification of slam severity. As the bow emerges prior to slamming the slam phenomenon may also be measured by a pressure capsule in the region of the forefoot. The pressure recorded will fluctuate as the bow moves vertically, but will only drop to the atmospheric value when the forefoot emerges. This in turn can be linked to a counter to give number of slams per hour.

The diagram (Fig. 3.1) illustrates a "recommended operating limit" based on sea trials under service conditions. The

PREDICTED OPERATING LIMIT DIAGRAM

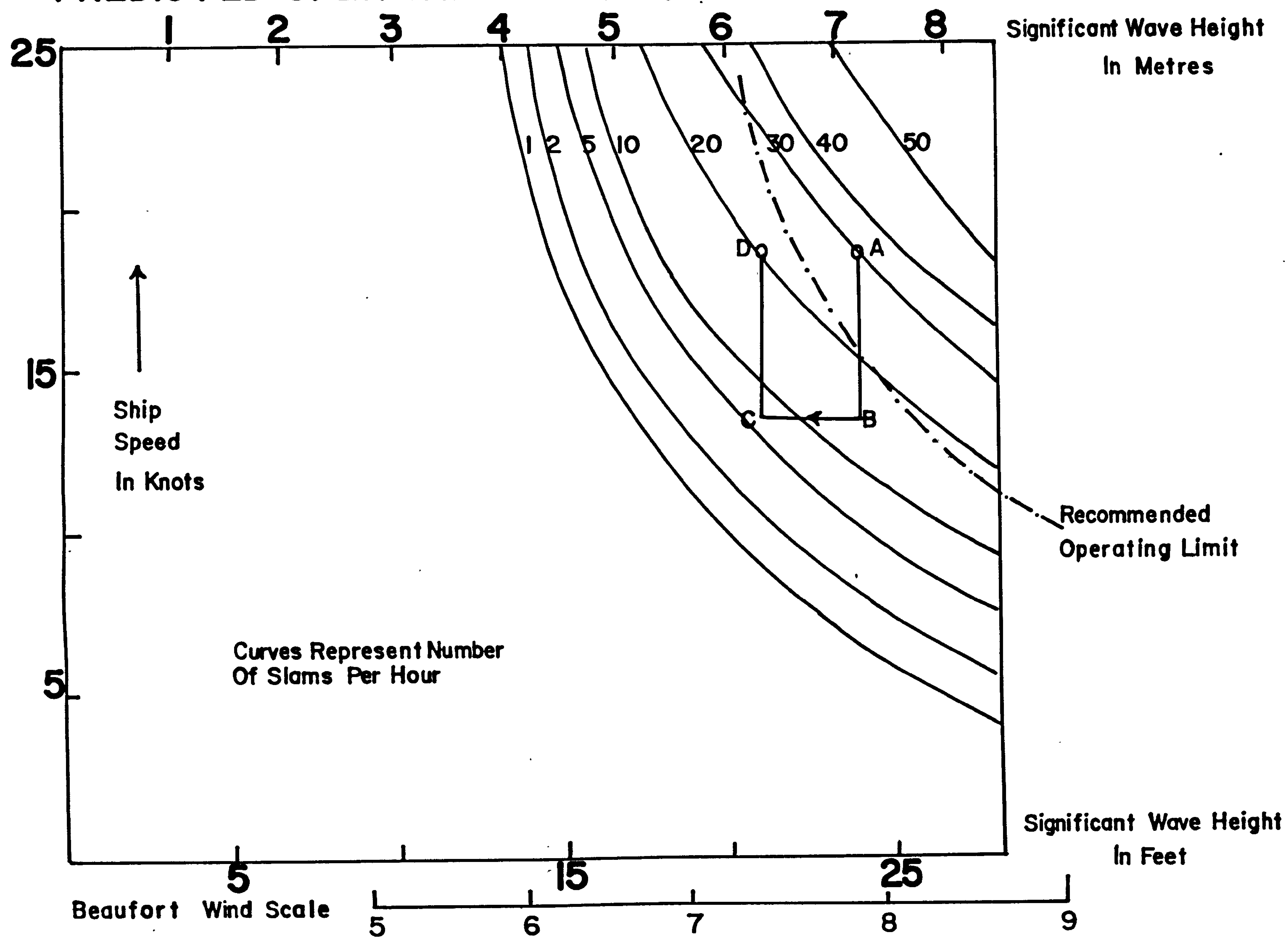


Fig. 3·1

vessel's normal sea speed is 25 knots. If the ship speed is 18 knots and the number of slams is 28 per hour (A), with significant wave height of 24.5 feet, then this count contravenes the accepted maximum and speed should be reduced to 14 knots. The number of slams should now reduce to about 15 per hour (B).

If the number reduces further to 8 or so per hour (C), assuming the sea state has now moderated, then an increase in speed to 18 knots again (D), will maintain the speed within the limit of acceptability.

These are arbitrary limits and the occasional hard slam can still lead to permanent damage, but the likelihood of such an occurrence while operating within the advised limits is greatly reduced.

This theory can be used and modified in practice by the ship's master to assist in decision making.

Manchester Liners have experimented with an anti-slamming device to warn watch-keeping officers when their ship is endangered, so that they may take necessary avoiding action, either altering course or reducing speed. This original work is now in the process of being focussed to a logical conclusion by the work of ROBERTSSON (*90*), at Plymouth and TAYLOR (*98*), of Lloyd's Register of Shipping.

Inevitably the decision leading to a voluntary reduction of speed by the ship's master depends on personal insight and experience in ship handling and therefore contains subjective elements.

AERTSSEN (*1 and 2*), deduced that shipping of water was, not surprisingly, the main reason for voluntary power reduction for cargo vessels in the fully loaded condition, whereas in a medium loaded condition racing of the propeller and wetness were equally considered. In the light condition racing and slamming are critical in a severe sea and advice from the engine room indicating where conditions are harmful to the engine may be necessary.

For other vessel types the relative importance of slamming, wetness and racing will differ. The purpose of this work is to ensure that these effects are related in some ship response indicator for use by ship's officers in navigating their vessels.

3.2.3 Ship losses

Today the number of ships lost from all causes is about one fifth of what it was towards the end of the last century. Of these a smaller percentage is lost through collision or shipwreck, but there is little or no improvement in the percentage lost by foundering. Obviously there exists combinations of weather, loading and economic pressures which are still too much for certain ships, despite improvements in design.

A total of 279 ships, amounting to 2,264,970 tons gross, were recorded as lost during 1979 in the Loss Book of the Liverpool Underwriters' Association. This is the highest annual figure for tonnage loss ever recorded exceeding the 1978 figure by 64.16%. (Until 1979, the 1978 figure was the highest on record). Tankers and bulk/combination carriers accounted for almost 65% of the total loss figure. Significantly 75% of the tonnage lost were registered in 4 countries - Cyprus, Greece, Liberia and Panama.

Number and tonnage of ships lost due to press of weather have increased annually over recent years and in 1979 amounted to 59 ships totalling 405,174 tons gross. A further 37 ships totalling 95,115 tons gross were lost through founderings and abandonments where it must be assumed that press of weather played a significant part. Three of the aforementioned vessels were over 30,000 tons gross each.

These statistics alone indicate little room for complacency in ship operation. There is little doubt that planning avoidance of adverse weather at the outset of a voyage would reduce these appalling losses.

3.3 Ship Performance

3.3.1 Data collection

Before it is possible to weather route a ship effectively it is necessary to establish how that particular vessel will behave over a range of draughts and trims, in differing sea conditions, embodying the effects previously catalogued.

Some researchers, BONEBAKKER (*15*), CLEMENTS (*19*), have obtained data from log extracts, a method often used by commercial shore based weather routeing companies. Others AERTSSEN (*2*), SCOTT (*92*), collect data whilst on board, ideally in a non-serving capacity. The former method incorporates the several inaccuracies of many observers whilst using a large data set. The latter data is generally obtained over a shorter time period but is considered to be more accurate and therefore a smaller spread will obtain in a regression analysis.

It was decided to use the latter method to give an indicator of ship performance on two entirely different ship types:

(i) S.S. GONDWANA, a steam turbine V.L.C.C.

(ii) M.V. DART ATLANTIC, a motor vessel and container ship

These two vessels are quite different in design, type, operation, trade and behaviour.

The differences are readily obvious to mariners but to give an example. The GONDWANA has a loaded displacement of 252,000 tonnes and a ballast displacement of 136,000 tonnes, due to the practice of the tanker trade of largely a uni-directional freight earning capacity. The DART ATLANTIC as a container vessel is concerned with a two way flow of cargo and thus is subjected to a very much smaller range of displacements, 38,900 tonnes to 33,700 tonnes over the period of observation undertaken. This enables the data collected to be analysed as representative of the behaviour pattern of the vessel for the small range of displacement. The GONDWANA data has to be dealt with in two sets for the laden and ballast conditions separately as the massive range of displacement prohibits commonality.

The key data sets were obtained by observations on board the two vessels and reinforced by log book data which was considered to be reliable from previous voyages.

Data were obtained by the author on a thirty-day voyage in a serving capacity as chief navigating officer on board the S.S. GONDWANA of Safmarine Lines Ltd. in the Indian and Atlantic oceans. Further data was obtained by Mr. Norman Babbedge on a twenty-one-day voyage on board the M.V. DART ATLANTIC of Bibby Lines Ltd. in the North Atlantic Ocean. Mr. Babbedge collected the data whilst in a "non-serving" capacity and under my direction as his research Director of Studies. I am deeply indebted to him for this work and for the invaluable work he did on the computer programmes used to subsequently analyse these data.

Speed is obviously the dependent variable which is to be analysed with respect to the independent variables of wind and/or sea and power.

To carry out a voyage analysis, it is necessary to know the speed of the ship as accurately as possible. There are two main methods of speed determination:

(a) distances obtained by navigation, giving speeds over the ground

(b) distances obtained from some form of log, giving speeds through the water

The first method is affected by ocean currents, and for this reason alone it cannot be reliably used.

The second method is widely regarded as inaccurate, but it will be shown that some of the inaccuracies can be corrected for.

Wave height and direction were estimated visually for both vessels and swells recorded separately. An accurate assessment of wave height is one of the most important aspects of the data collection exercise since the square of wave height is used in analysis magnifying any error in estimation.

Wind speed was instrumentally obtained from the DART ATLANTIC from a fitted mast anemometer recording relative wind speed and its direction off the bow. The sensor was fitted 36m above the water giving a wind speed some 1.15 times the speed at 10m (WMO no. 446). Since a large proportion of the relative wind speed is a constant amount caused by the ship's speed, this factor was ignored. Aboard the GONDWANA relative wind speed was measured by a hand-held anemometer on the bridge wing together with an estimation of relative wind direction.

Speed-power relationships obtained from the acceptance sea trials of both vessels indicated that speed is very nearly linear with $\log_e P$ over the operational range. Therefore $\log_e P$ was used initially as an independent variable. Power was obtained for the DART ATLANTIC by using an A.E.I. torsion meter.

It is helpful to have another set of speeds as a basis for comparison; the speeds used for this purpose are obtained from navigational distances. The method of analysis outlined below was originally used by SCOTT (*92*).

From the deck log book the following details were extracted, covering a period of several months:-

(1) the distance travelled over the ground, from noon-to-noon measured by some position fixing method (sextant, decca, loran):- D_{NN}

(2) the distance travelled through the water over the same period as measured by the log:- D_{sl} or D_{ch}

(3) the mean wind speed during that period:- V_w

(4) the mean wind direction off the bow:- α

(5) the wave height and direction off the bow,

if available:- H_W and μ_W

(6) the draught

From these, the ratio D_{NN}/D_{s1} is used as the dependent variable in regressions against various wind functions, draught and time.

3.3.2 Data Analysis

In order to find the variation of a dependent variable such as ship's speed with parameters which are believed to affect it, previous results and any relevant theory must be used, at least as initial selectors of the independent variable forms.

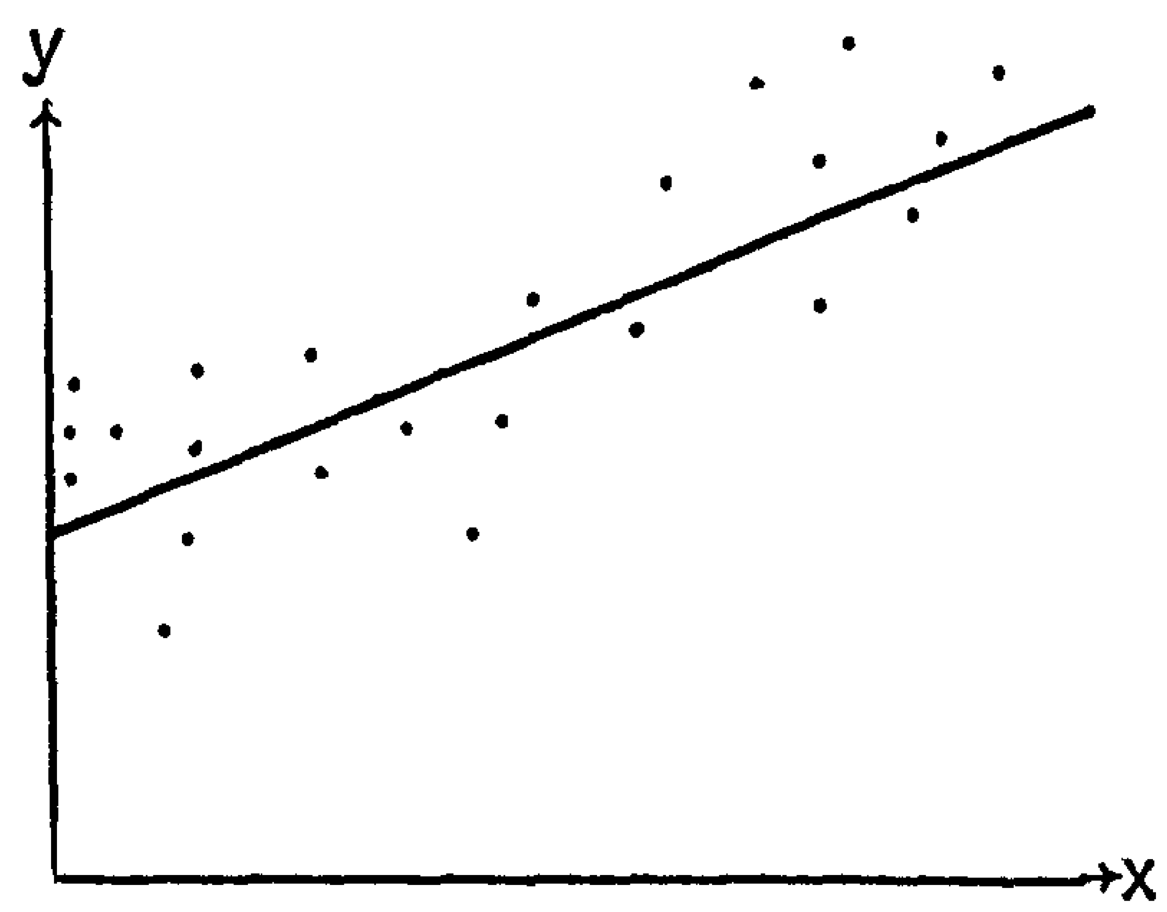
During analysis, several regressions are carried out, each of which is used in deciding which independent variables should be included in the next. The whole operation is aimed at reducing the residual standard error subject to the condition that the final result contains no unscientific or non-significant terms.

The success of a regression equation is measured by the residual standard error, which represents the amount of dependent variable variation which is unaccounted for by the regression equation. The errors quoted in the regression equations in this thesis are the residual standard errors.

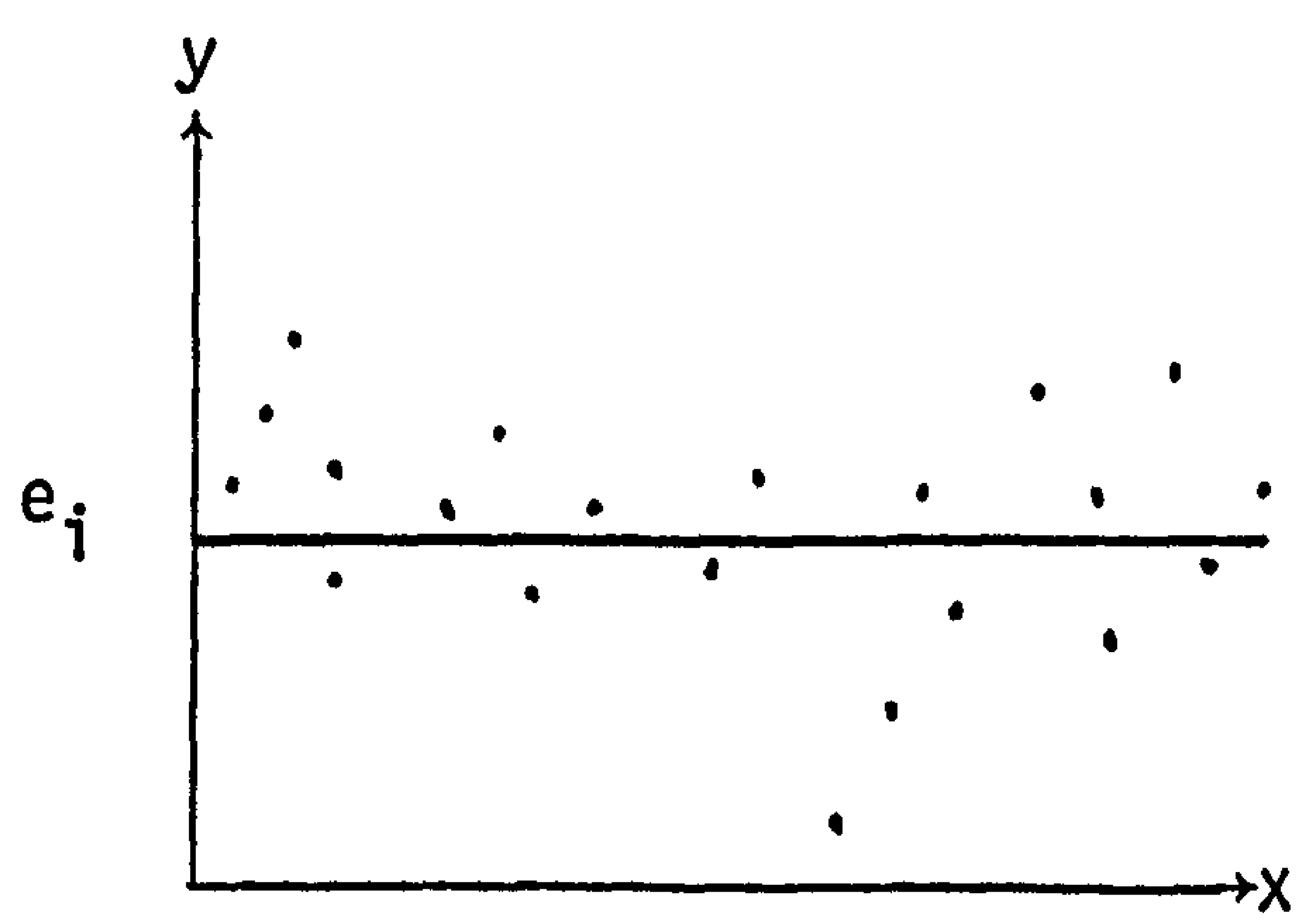
The 5% significance level is normally used as an acceptance limit, although the 10% level may be used in exceptional circumstances.

The residuals e_i can be used to find further independent variables, or variables whose fit is not linear.

e.g. if in a simple regression the points were of the form:-



then the deviations from the regression line $y = a + bx$ would appear as:-



indicating a more complicated polynomial fit. In this simple single-variable case this is immediately apparent from the initial scatter diagram, but this would not be true for multiple regression.

The plotting of these residuals plays a very important part in choosing the exact functions to be used as independent variables. Residuals can also pinpoint observations with a large deviation from the regression plane. These can be checked, and if a very good reason is found for the error, such as faulty equipment, they can be removed. Observations with large residuals must not be removed simply because they have large residuals.

Multiple regression is an extension of linear regression used when it is required to estimate y in terms of any number (p) of independent variables. The fit is of the form

$$y = a + b_1x_1 + b_2x_2 \; ..... + b_px_p$$

$$= a + \sum_{j=1}^{p} b_jx_j$$

The fit makes $\sum_{i=1}^{n} (y_i - a - \sum_{j=1}^{p} b_jx_j)^2 = \sum_{i-1}^{n} e_i^{\,2}$

a minimum and leads to

$$a = m_y - \sum_{j=1}^{p} b_jm_{x_j}$$

and

$$b_j = \frac{D_p \text{ with } y \text{ replacing } x_j \text{ in the } j^{th} \text{ column}}{D_p}$$

where D_p is the covariance determinant. (See SCOTT (92)).

The t-values* are given by

$$t_j = \frac{|b_j|}{\sqrt{\dfrac{\{(\overset{1}{\Sigma}\, y^2 - \overset{p}{\Sigma}\,(b_j \overset{1}{\Sigma}\, yx_j)\}\ (D_p \text{ with } j^{th} \text{ row and } j^{th} \text{ column omitted})}{(n - p - 1)D_p}}}$$

which are t-distributed with n-p-1 degrees of freedom.

The square of the standard error of the estimate is an unbiased estimate of the residual deviations of the population from the regression plane of the same form which would have been found from the population. (n-p-1) in the denominator is required for the achievement of this property, which makes residual standard errors valid measures of the success, as dependent variable predictors, of the various regression forms used. (Details of the Multiple Regression programme are given in Appendix I).

1.96 times the standard error represents the limits outside of which about 5% of the quantities e_i lie.

---

* *The t-value assesses whether or not the value of b (as defined in the programme by b_j above) is likely to be indicative of a real variation of y with x in the population which the sample represents. This may be summarised as e.g. "b is significant at the 1% level" where $t_{1\%} < t < t_{0.1\%}$.*

Table 3.2

Variables available for regression programmes

Variable No.	Abbreviation	Units	Description
1	V_{ch}	knots	Vessel speed by log
2	V_R	knots	Relative wind speed
3	β	degrees	Direction off bow of V_R
4	α	degrees	Direction off bow of true wind
5	V_W	knots	True wind speed
6	μ_W or μ_S	degrees	Direction off bow of waves or swell
7	p	metric h.p.	Horsepower of vessel
8	V_C	knots	Raw speed of vessel corrected for power [α log error]
9	H_W or H_S	ft(m.)	Wave height or swell height
10	θ	centi-grade	Sea temperature
11	Δ or T	tonnes/ft	Displacement or trim
12	t		Time

A total of 60 sets of observations were collected on board the GONDWANA whilst for the DART ATLANTIC regressions were carried out on 48 sets of observations collected over a 3 week period. The data samples contained the following variables:-

V_{ch}, V_R, β, H_w, μ_w, H_s, μ_s, P, θ, Δ, Trim, Time

organised into variable numbers contained in Table 3.2.

The best estimator of the ship's speed obtained after correcting for log error was:-

$$
\begin{aligned}
V_{est_1} &= 19.87 + 6.38 \frac{(\ln P - \ln 20{,}000)}{26.0} - \\
&\quad 10.2 \frac{V}{p} H_w^{2} \frac{[\cos^3(\mu/2) + 0.3]}{9.22} + \\
&\quad 0.04 \frac{(\theta - 12)}{5.15} - 0.00015 \frac{(\Delta - 37000)}{3.31} \\
&\quad \pm 0.28 \qquad \qquad \ldots\ 3(v)
\end{aligned}
$$

$$
\begin{aligned}
V_{c_2} &= V_{ch_{cl}} + 10.2 \frac{VH_w^{2}}{p} [\cos^3 (\mu/2) + \\
&\quad 0.3] - 0.04 (\theta - 12) + \\
&\quad 0.00015 (\Delta - 37000) \qquad \qquad \ldots\ 3(vi)
\end{aligned}
$$

represents the measured speed corrected for log error, a displacement of 37,000 tonnes, no waves and a sea temperature of 12^{o}C. In the absence of any residual standard error these points should all lie on the line

$$V_{est_1} = 6.38 \ln P - 43.31$$


M.V. DART ATLANTIC RAW DATA
22
21
20
19
18
17
16
SHIP SPEED IN KNOTS
Vch
Vest2=6·44 ln P-43·85...... EQ.3(IX)
SHAFT HORSE-POWER
12
14
16
18
20
22
24
S.H.P. x 10-3

Fig. 3·2

which is the calm water speed-power relationship at a displacement of 37,000 tonnes and a sea temperature of 12^{o}C. The slope of this line obtained on trials (displacement unavailable) was 7.1.

No significant variation of the ship speed with wind speed could be found. However, when the term in $V_W \cos\alpha$ was included in the log speed correcting equation the following result was obtained:-

$$V_{est_2} = 19.93 + 6.44 \underset{26.0}{(\ln P - \ln 20{,}000)} - 10.2\frac{VH_W^{\,2}}{P}$$

$$(\cos^3 \underset{9.49}{(\mu/2) + 0.3)} - 0.28\frac{V}{P}\Big(\big(\frac{V_R}{V}\big)^2_{3.08} \cos\beta - 1\Big)$$

$$+ 0.04 \underset{4.74}{(\theta - 12)} - 0.00012 \underset{2.69}{(\Delta - 37{,}000)}$$

$$\pm 0.27 \qquad \ldots\ 3(vii)$$

This result, containing a reduction in speed with head winds, an increase in speed with tail winds, and a small reduction in speed for following seas, and for this ship it gave the lowest residual standard error. As for equation 3(vi)

$$V_{c_2} = V_{ch_{c2}} + 10.2\frac{VH_W^{\,2}}{P} \quad (\cos^3 (\mu/2) + 0.3) +$$

$$0.28\frac{V^3}{P}\Big[\big(\frac{V_R}{V}\big)^2 \cos\beta - 1\Big] - 0.04\,(\theta - 12) +$$

$$0.00012\,(\Delta - 37000) \qquad \ldots\ 3(viii)$$

represents the measured speed corrected for log error (including $V_W \cos\alpha$) a displacement of 37,000 tonnes, calm weather, and a sea temperature of 12^{o}C. The points should lie about the line


M.V. DART ATLANTIC
V_{ch} Corrected for Displacement (37000 tons), Calm Weather,
Sea Temperature (12°C), and Log Error
From Eq.6.1.3.
Regression Line
$Vest_2 = 6{\cdot}44 \ln P - 43{\cdot}85$ ..... EQ. 3(IX)
SHAFT HORSE-POWER
SHIP SPEED IN KNOTS
V_{C2}
22
21
20
19
18
13
14
15
16
17
18
19
20
21
22
23
24
25
S.H.P. x 10^{-3}

Fig. 3·3

$$V_{est_2} = 6.44 \ln P - 43.85 \qquad \ldots 3(ix)$$

Figs. 3.2 and 3.3 show the raw data and V_{c_2} respectively plotted against power. On both graphs, the curve represented by equation 3(ix) is drawn for reference, and they show clearly the reduction in scatter obtained using equation 3(viii).

The estimated speeds calculated from equations 3(v) and 3(vii) are plotted against Beaufort number in Fig. 3.4. For convenience, the speeds in calm weather have been adjusted to 20.0 knots. These calculations use the empirical relationship

$$H_W = 0.075 V_W^{3/2} + H_S \qquad \ldots 2(xxiii)$$

derived by SCOTT (*91*), and Fig. 3.4 shows that equation 3(vii) gives a curve of the expected shape.

Neither trim nor time showed any significance in the regressions. The GONDWANA data was similarly analysed in two discrete sets as previously defined. The log book data (Appendix II) were then treated to facilitate analysis. All speeds were calculated between navigational observations and the data setted as in the sample shown in Appendix III.

It is essential that a record of data is kept linking three aspects:

M.V. DART ATLANTIC - SPEED vs BEAUFORT NO.

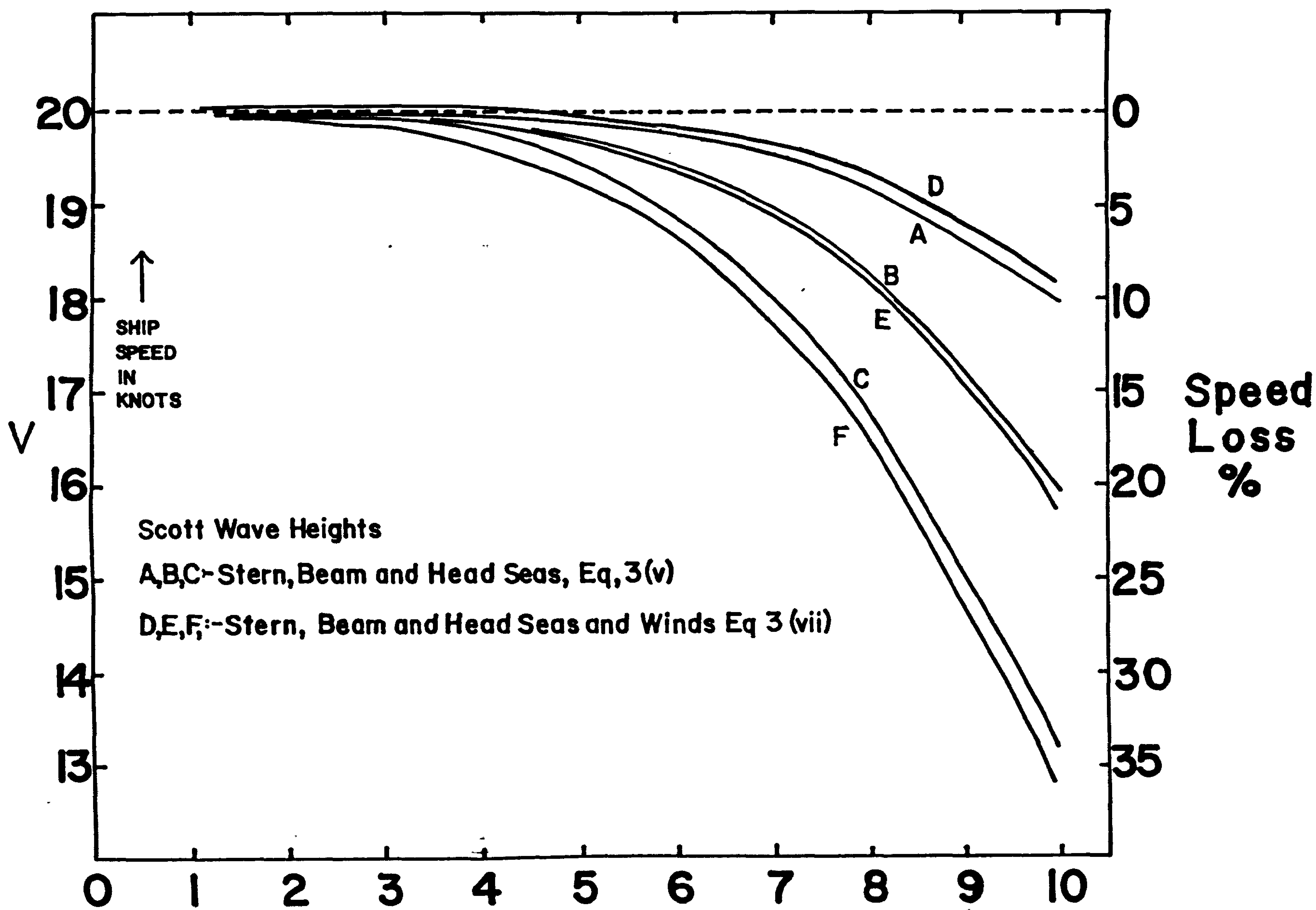


Fig. 3·4

1. Ship data:

   draught information, displacement, stability information (metacentric height, etc.)

2. Sea data:

   Wave heights, swell, current information, wind direction and force.

3. Ship behaviour:

   Speed made good, amount of rolling and pitching and/or slamming.

In general this information is available in the mate's deck log, and in a more concise form in voyage abstracts depending on the custom and requirements of various shipping companies.

Should insufficient data be available as described above the following information should be collected. Suggested headings are:

Ship Behaviour			Engine reduction below service speed
Course	Speed made good	Ship movement	
270	10 kts	Pitching heavily, no slamming	Nil

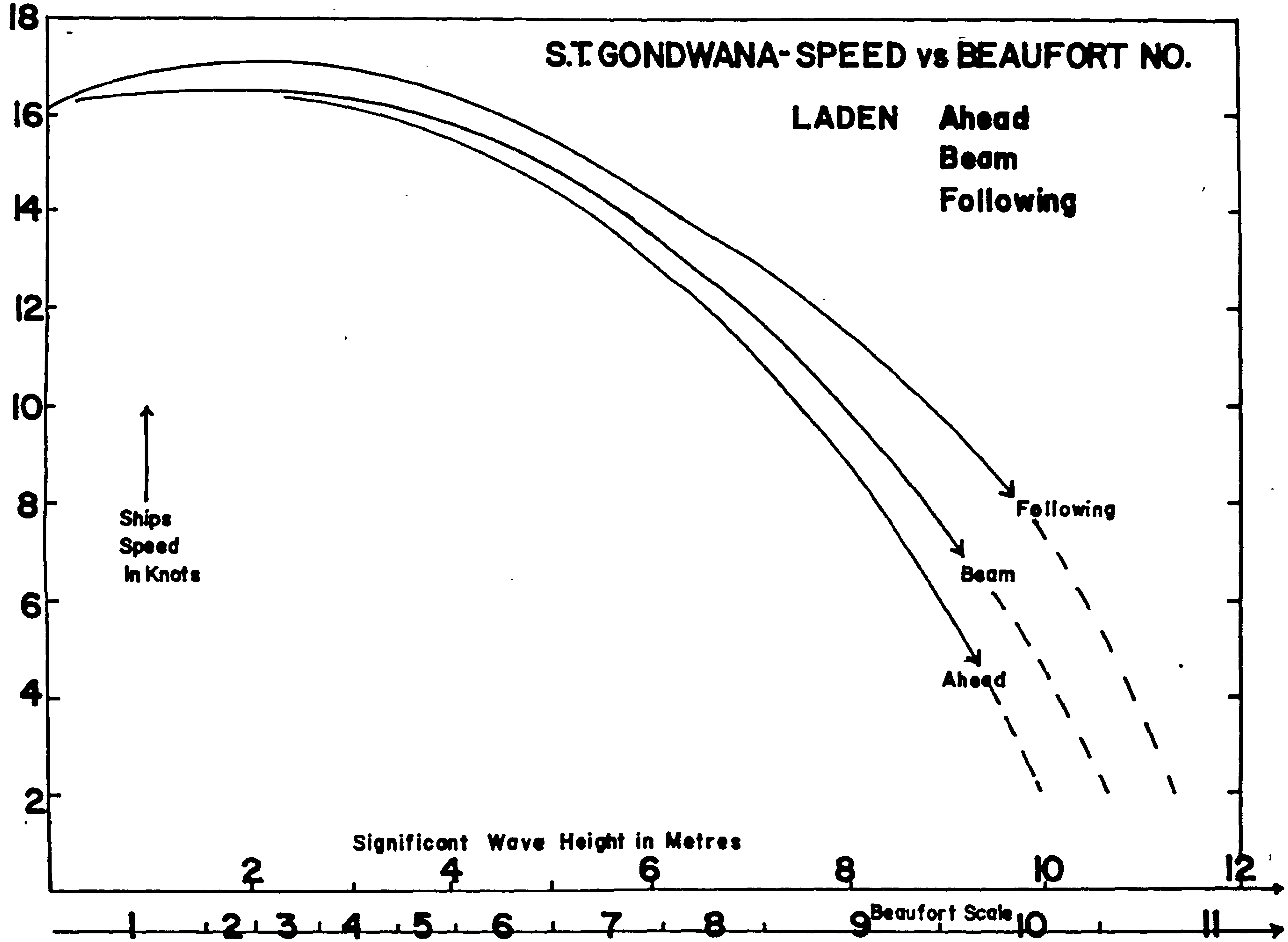

S.T. GONDWANA - SPEED vs BEAUFORT NO.
LADEN Ahead
Beam
Following
Ships
Speed
In Knots
Following
Beam
Ahead
Significant Wave Height in Metres
Beaufort Scale
18
16
14
12
10
8
6
4
2
2
4
6
8
10
12
1
2
3
4
5
6
7
8
9
10
11

Fig.3·5

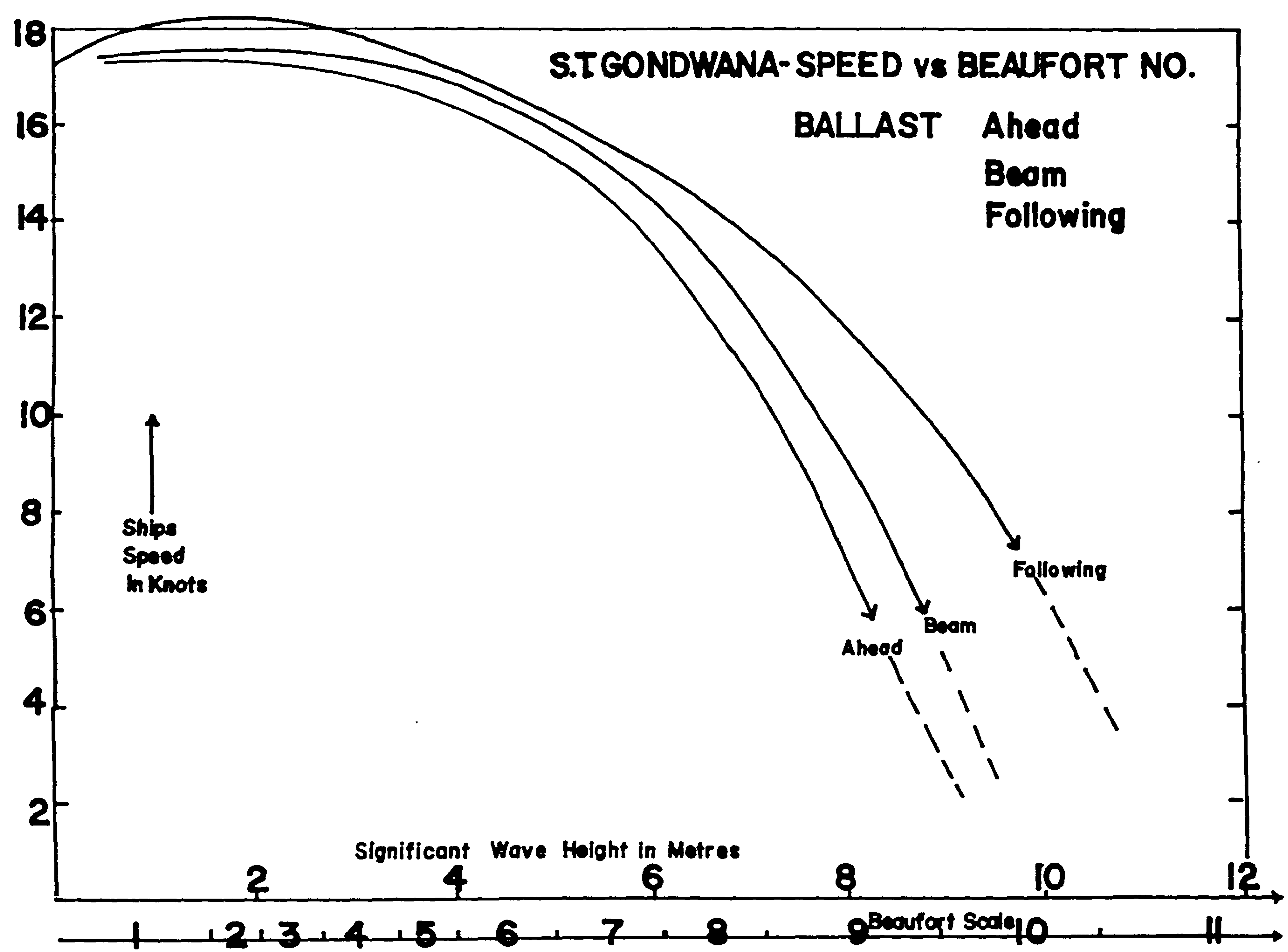

S.T GONDWANA-SPEED vs BEAUFORT NO.
BALLAST Ahead
Beam
Following
Ships
Speed
in Knots
Following
Beam
Ahead
Significant Wave Height in Metres
Beaufort Scale
18
16
14
12
10
8
6
4
2
2
4
6
8
10
12
1
2
3
4
5
6
7
8
9
10
11

Fig. 3·6

Weather

Wind				Sea		
Direction	Force			wave ht.	swell	current
	ahead	beam	following			
270	8	-	-	6m.	-	-

This information is analysed in order to express the effect of weather on the ship. Two circumstances may contribute to effective speed loss.

(1) at a given engine setting - the general service speed, ship speed will decrease as sea conditions deteriorate.
(2) in a given state of sea, usually corresponding to a minimum of Force 6 from ahead, ship motions may become so violent that speed and power are on the limit the ship can safely maintain. If the weather deteriorates further the master intervenes and reduces engine revolutions, deliberately diminishing power in order to ease motions.

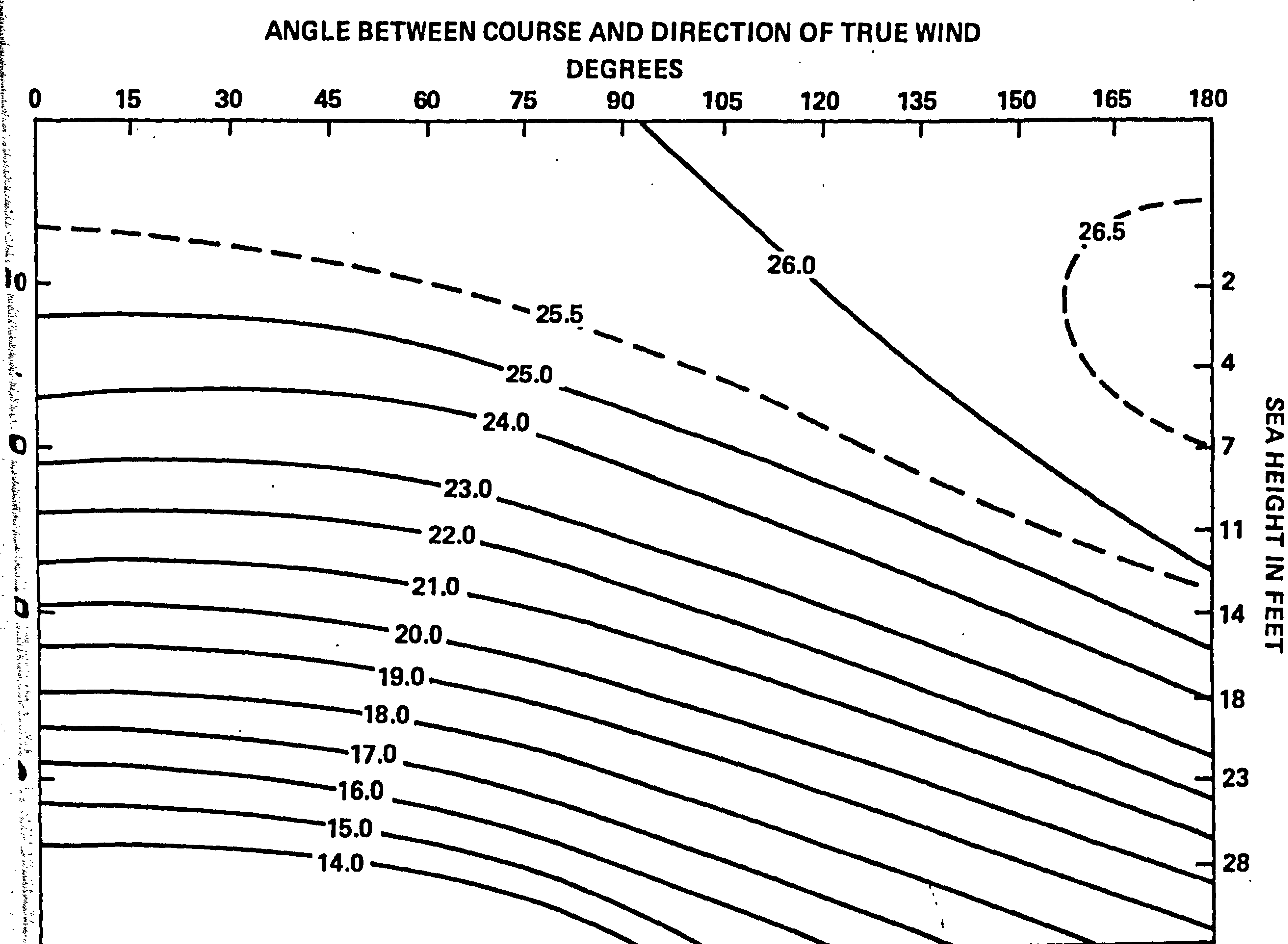
In the case of the GONDWANA no engine reductions were ordered and all data collected related to condition (1), as used in the analysis.

Multiple regression analysis was used as in the DART ATLANTIC case to produce the performance curves shown in Figs. 3.5 and 3.6

TEXT BOUND INTO

THE SPINE

PERFORMANCE CURVE FOR 26 KNOT CONTAINER SHIP



ADDITIONAL REDUCTION DUE TO CROSS SEAS DURING WIND SHIFT

AVERAGE WIND	REDUCTION IN KNOTS
15	0.4
20	0.7
25	1.0
30	1.6
35	2.1

FIGURE 3.7

3.3.3 Ship Performance Curves

The data from the DART ATLANTIC and the GONDWANA have been embodied in the curves shown in Figs. 3.4 - 3.6. It should be noted, however, that there are many and varied methods of representing the results of such analysis. For example, Ocean Routes of California (*82*), have built up an extensive library of ship behaviour related to ship types and plot the resultant speeds as a set of curves using the variables of wave height and angle between course and direction of true wind in degrees (Figure 3.7).

K.N.M.I. de Bilt use a polar diagram of the speed performance of a ship (*70*), (*71*). These figures are obtained from theoretical assumptions, they have the advantage of being usable in a routeing exercise on a new vessel or a vessel where retrospective performance data is unavailable.

A visual comparison of the two sets of curves for the GONDWANA, loaded and ballast with their very differing gradients, highlight the variation in response characteristics even in the same vessel. This serves to illustrate the weakness in any generalised set of curves for use for differing vessels.

The format I have used is well tried and tested and I believe is well suited for use on board ship. The curves are easy to construct without using the multiple regression analysis techniques in this work. A simple scatter diagram will produce satisfactory results, bearing in mind that it is the relative difference in behaviour of the vessel that is important.

Obviously extensive computations by computer on large data sets will refine results. I believe that it is important for the ships' officers to understand the curves they are to use and the majority of officers will readily acknowledge the significance of setting the data into ahead, beam and following seas.

4. FACSIMILE RECEPTION

4.1 Facsimile Receivers

4.2 Transmission Network

4.3 Meteorological Facsimile Broadcasts

4. FACSIMILE RECEPTION

4.1 Facsimile receivers

The marine facsimile receiver is ostensibly a device for the reception and display of meteorological and oceanographic data.

Various principles of recording and transmission are used; the latest models use the sub-carrier frequency modulation (s.c.f.m.) or frequency shift keying (f.s.k.) methods of radio transmission - not amplitude modulation as used in normal transmission (frequency of signal varies to change modulation and amplitude is constant). This gives a much clearer signal, relatively static free transmission, and better reception on board.

Moist electro-sensitive recording paper is drawn at constant speed between a stainless steel writing edge and a rotating helix. Current is passed through the paper at the point of contact, causing a chemical action which marks it. The density of marking depends upon the magnitude of the current, which is controlled by the received signal.

The rotation of the helix and movement of the paper together cause the point of contact to scan the paper in a series of horizontal lines. As the frequency varies, so the marking varies, and, in this way, a facsimile of the original chart is built up in clear black and white. (The originals are constructed by the normal dye-line process which lends itself to transmission).

The scanning density on some machines can be varied from

96 lines per inch (4 lines per mm), corresponding to an index of co-operation of 576, for charts which embody detailed information such as a surface analysis with station reports, to half of this density, i.e. an alternate line scanning technique for less complex requirements such as upper air information.

For standardisation purposes, WMO specified three speeds for weather chart transmissions - 60, 90 and 120 rpm.

Thus, when the transmitter is operating at a scanning density of 2 lines per mm, at a rate equal to a speed of 60 rpm, it takes 20 minutes to transmit and receive a weather chart approximately 48 cm by 30 cm (at 90 rpm 15 minutes and at 120 rpm 10 minutes).

WMO has also developed minimum technical specifications for facsimile recorders and receivers.

The receivers are intended for automatic unattended operation. The whole recorder requires only the connection of an A.C. power supply with an aerial, for the receiver. Apart from the roll of sensitised paper the only item requiring replacement at intervals is the inexpensive writing edge.

Modern receivers incorporate pre-tuned crystals for particular frequencies. It should be noted that such a machine should also include the facility to off-tune up to 1.5 KHz in order to avoid jamming by the numerous commercial stations on the American coast.

METEOROLOGICAL FACSIMILE TRANSMITTING STATIONS　　STATIONS DE TRANSMISSION METEOROLOGIQUE PAR FAC-SIMILE

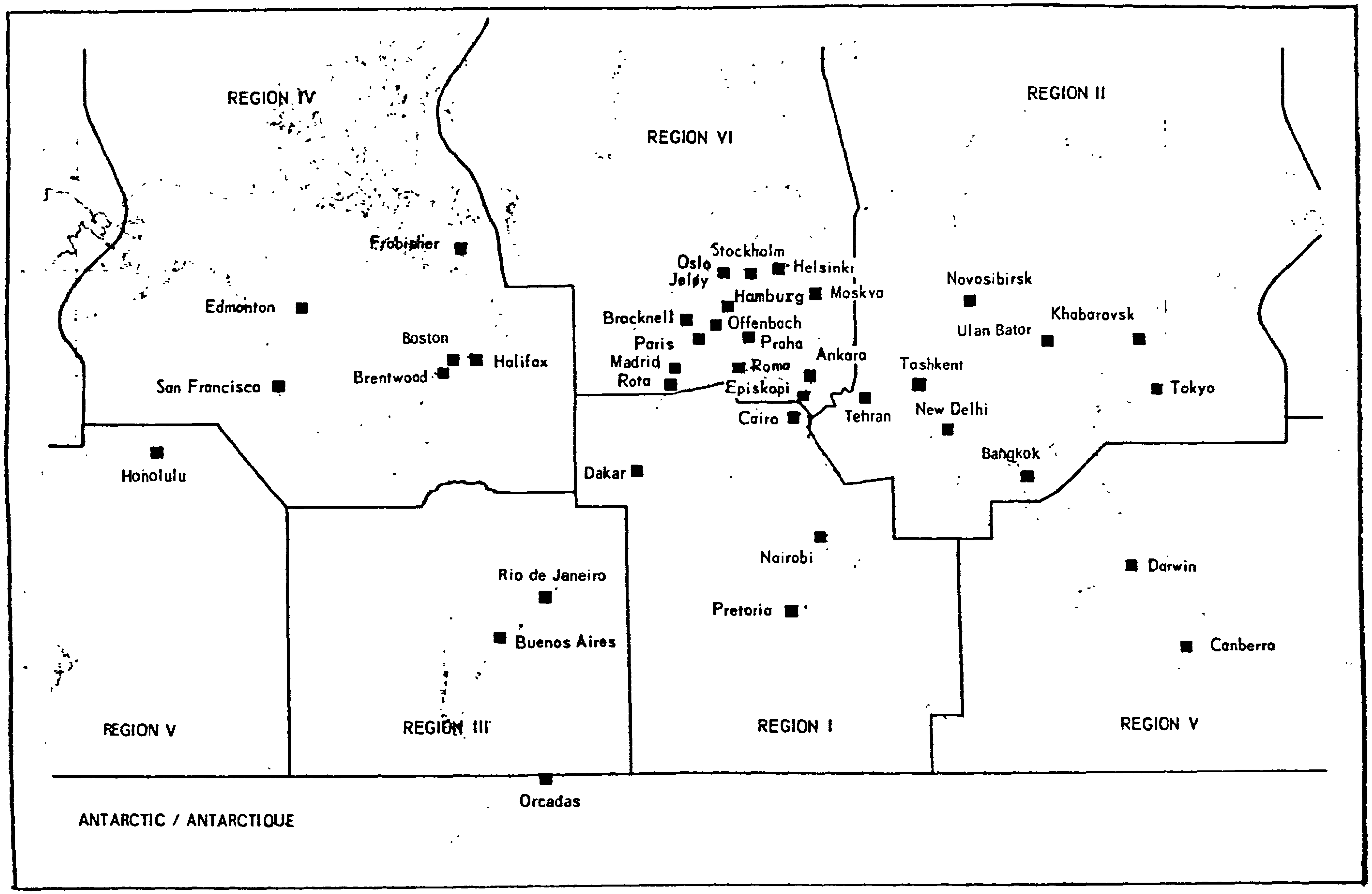


Fig. 4.1

Facsimile reproduction is absolute, exact and not limited to isolated groups and specified co-ordinates, as are W.T. messages. A continuous flow of charts other than isolated surface analysis is available.

The facsimile machine is a device which makes the possibility of weather routeing from on board ship a reality. This facility provides detailed data for analysis in a routeing model; without it, decisions on storm avoidance and storm tracks would, of necessity, be largely based on guess work.

4.2 Transmission network

The Figure 4.1 shows the meteorological facsimile transmitting stations within the agreed World Meteorological Organisation (WMO) regions as published in WMO/OMM - No. 9, Vol. D, Part F_{ii}. It should be noted that the North Atlantic Ocean is particularly well served. Furthermore, the information given is based on a vast source of data supplied from shore station, ocean weather ships, aircraft and merchant vessels. The density of data collection, both for surface and upper air purposes for the North Atlantic and its bordering coastlines is far in excess of that available for other oceans. It follows that the service provided from this original data will reflect the size of data bank.

There is almost an embarrassment of riches as far as facsimile stations go, particularly on the western seaboard of Europe. It has been my experience that the Offenbach Station of West Germany provides a comprehensive and efficient output of charts. A comparable service is also provided by GFA, Bracknell.

4.3 Meteorological Facsimile Broadcasts

Appendix IV lists the charts available from transmissions by station GFA, Bracknell. Information given includes

(i) Time of broadcast

(ii) Drum speed in revolutions per minute

(iii) Index of co-operation, for picture density

(iv) Chart or data designator group to distinguish analyses, forecasts, surface and upper air data (respectively A, F, S and U)

(v) Geographical Indicator of the chart origin

(vi) Map areas, whereby a transmitted letter corresponds to an area covered. Scale and projection may also be given.

The charts available include:-

<u>Surface</u>

(a) Surface analysis with observations

(b) Surface prognosis (12, 18, 24, 36 and 72 hours)

(c) Change of pressure charts (3 and 24 hours)

<u>Upper Air</u>

(d) Constant pressure chart analysis) (850, 700, 500,
Constant pressure chart prognosis) 300, 200, 100 mb)
(24 hr, 48 hr, 72 hr and 96 hr prognosis available for 500 mb surface)

(e) Relative topography 500/1000 mb layer thickness charts

(f) Wind plottings for upper levels

(g) Lapse rates of the environment (e.g. STUVE diagrams)

(h) Tephigrams for selected stations

Sea

(i) Distribution of ice and iceberg information

(j) Synoptic and prognostic wave charts

Miscellaneous

(k) Nephanalysis; pictorial representation of satellite information

(l) Sea surface temperature analysis (ten day basis)

The stations transmitting charts adhere to international symbols and codings and reception from any source conforms to these agreed WMO standards.

The charts as listed are readily available from several of the stations providing an adequate coverage of the North Atlantic Ocean.

The routeing model to be formulated in Chapter 6 will have the natural constraint provided by these data.

5. MIDDLE LATITUDE DEPRESSIONS

5. MIDDLE LATITUDE DEPRESSIONS

5.1 Baroclinic Zone

5.1.1 Baroclinic Instability

The weather routeing principle as outlined is only possible in a sea area which experiences changing patterns of weather. Thus it has limited application to the comparatively regular wind and sea states of the trade wind zones and indeed to the ocean areas dominated by a monsoon. It will prove most rewarding in its application to ships traversing oceans within the baroclinic zone of middle latitudes. It is thus advantageous to understand some of the features of baroclinic instability and the baroclinic wave. Instability is a "normal" feature of atmospheric motion. The meaning of "unstable" in this context has been defined by EADY (*29*). Thus if the initial field of motion be given, the final field of motion, after a given interval of time, is determined precisely by the equations of motion, continuity, and radiation, together with the appropriate boundary conditions. If we consider a slightly different (perturbed) initial state, the new final state, after the same interval of time, will be determined in a similar manner. The stability or instability of the motion depends on the behaviour of the resulting change (perturbation) in the final state as the time interval is increased. If the final perturbation remains small for all time for ALL possible initial perturbations, the motion is stable. If, on the other hand, the perturbation grows at an exponential rate for any possible initial perturbation the motion is unstable.

In middle and high latitudes this latter case is evident and has been termed baroclinic instability.

It can be shown quite simply from the zonal component of the momentum equation that the large scale eddies must be responsible for the maintenance of the surface winds with both meridional and zonal components evident as they are.

Thus

$$\frac{Du}{Dt} - fv + \frac{1}{\rho}\frac{\partial P}{\partial x} = 0 \qquad \dots 5(i)$$

becomes

$$\frac{Du}{Dt} = fv \text{ when integrated around a parallel of latitude}$$

$$u = fy \quad \text{as } v = \frac{Dy}{Dt} \qquad \dots 5(ii)$$

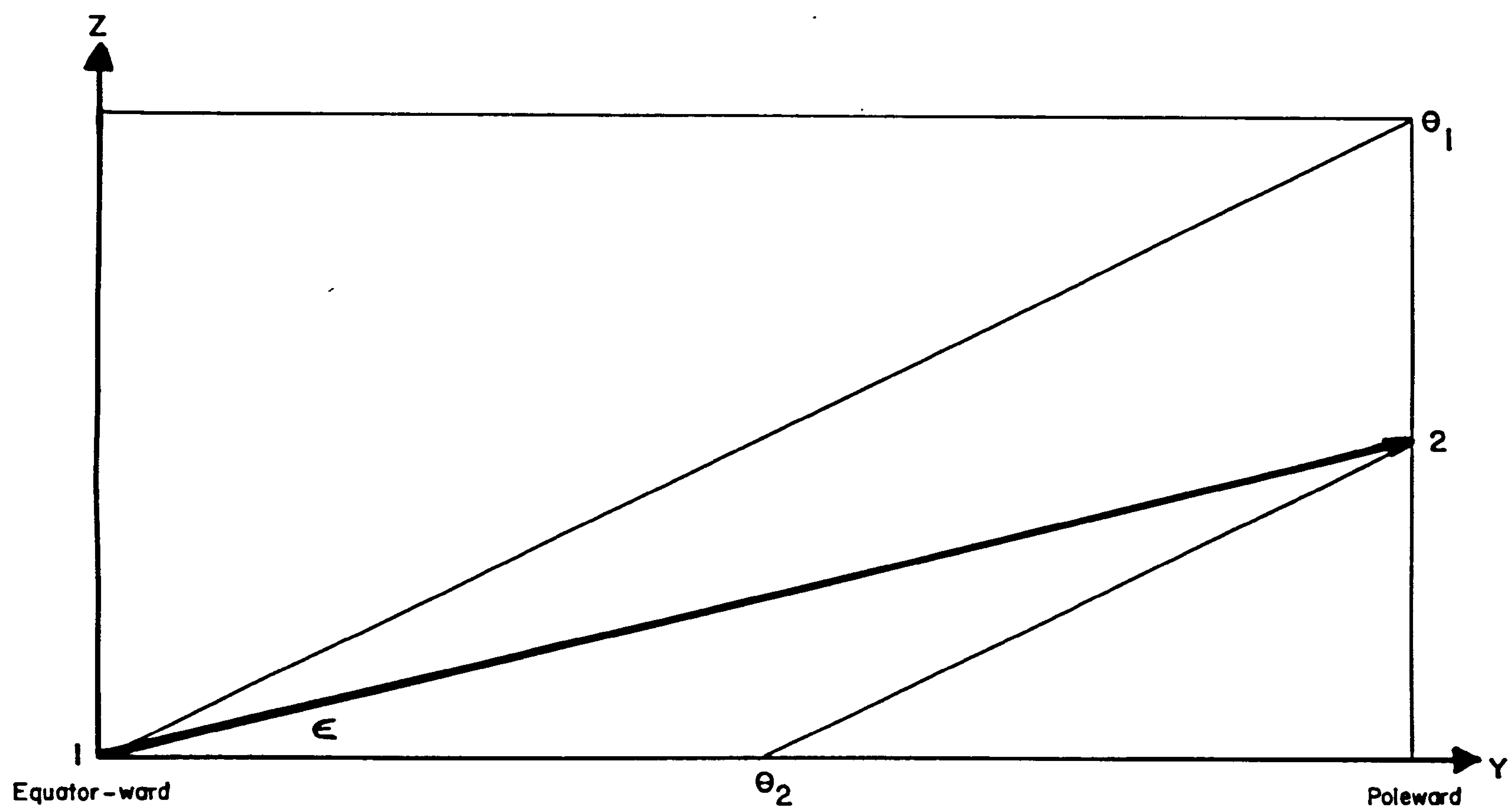
in middle latitudes with $u \simeq 10ms^{-1}$ a distance of only 100 km is necessary to conserve angular momentum and zonal flow.

This balances the temperature gradient across the baroclinic zone arising from the heat source of the tropics. However, if air is moved polarwards at one point and equatorward at another, the momentum budget integrated zonally would still balance and a motion of wavelike character (as observed) result with localised (meridionally) convective overturning to generate eddy wave energy.

5.1.2 Eddy Kinetic Energy

The kinetic energy of growing baroclinic waves is derived from the potential energy of the original flow, the eddies must re-arrange the system towards a state of minimum potential energy so that entropy must be transferred polewards and upwards.

Fig. 5.1 Parcel exchange for Eddy Kinetic energy.



Height-latitude cross section of the troposphere showing potential temperature θ increasing equatorward and upwards. Even though the system is stable for vertical convection, energy can be released if particles are exchanged along the thick solid arrow. (J.S.A. Green, (41)) Consider the change in Fig. 5.1 should parcel (1) exchange with parcel (2) adiabatically. The original pressure field is conserved and the consequent potential energy released can only become kinetic energy of the motion.

If V_1 and V_2 are the respective volumes and p_1 and p_2 the pressures, the law of adiabatic expansion demands that:

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma} \qquad (\text{where } \gamma = C_p/C_v)$$

C_p is specific heat at constant p

C_V is specific heat at constant V

The ratio of the masses of the two parcels is

$$\frac{M_2}{M_1} = \frac{(\rho_2 V_2)}{(\rho_1 V_1)} = \frac{\rho_2 p_1^{1/\gamma}}{\rho_1 p_2^{1/\gamma}}$$

As $\theta = T\left(\frac{p}{1000}\right)^{\frac{1}{\gamma}-1}$ where θ is potential temperature

then the ratio of the masses is inversely proportional to their potential temperatures

$$\frac{M_2}{M_1} = \frac{\theta_1}{\theta_2} \qquad \ldots 5(\text{iii})$$

equating

$$\theta_1 = \frac{C p_1^{1/\gamma}}{\rho_1} \quad \text{and} \quad \theta_2 = \frac{C p_2^{1/\gamma}}{\rho_2} \qquad \text{where } C = \frac{1}{R(1000)}^{\frac{1}{\gamma}-1}$$

Initial potential energy $= M_1 g Z_1 + M_2 g Z_2$

Final potential energy after exchange $= M_1 g Z_2 + M_2 g Z_1$.

Change in potential energy (ΔP.E.):

$$\Delta P.E. = M_1 g (Z_1 - Z_2) + M_2 g (Z_2 - Z_1)$$

$$= M_1 g (Z_2 - Z_1)\left(\frac{M_2}{M_1} - 1\right)$$

$$\Delta P.E. = M_1 g (Z_2 - Z_1)\left(\frac{\theta_1 - \theta_2}{\theta_2}\right) \qquad \ldots 5(iv)$$

Suppose each parcel acquires a typical velocity $\underset{\sim}{V}$ of kinetic energy from the change in potential energy.

$$\text{Kinetic energy gain} = \frac{1}{2} M_1 \underset{\sim}{V}^2 + \frac{1}{2} M_2 \underset{\sim}{V}^2 =$$

$$\frac{1}{2} M_1 \left(1 + \frac{\theta_1}{\theta_2}\right) \underset{\sim}{V}^2 \qquad \ldots 5(v)$$

equating 5(iv) and 5(v),

$$\left(\frac{\theta_1 + \theta_2}{2}\right) \underset{\sim}{V}^2 = g\Delta Z\Delta\theta$$

$$\underset{\sim}{V} = \left(\frac{g\Delta Z\Delta\theta}{\bar{\theta}}\right)^{\frac{1}{2}} \qquad \ldots 5(vi)$$

For the baroclinic zone $V = 14\ \mathrm{ms}^{-1}$.

This is then the maximum fluid velocity generated by a wave that experiences the interchange of air as shown, released through the redistribution of mass.

In practice the air is constrained to move nearly horizontally at both the ground and the tropopause, prohibiting the release of potential energy but nevertheless sharing the potential energy liberated by the less constrained central parcels. This effect can be taken into account by an optimum factor (after GREEN (*40*) and EADY (*29*), which in effect reduces the maximum energy release value by $1/\sqrt{3}$ to some 10 ms^{-1} wave velocity as observed).

GREEN (*41*), has evaluated the capability of these growing baroclinic waves as a transfer mechanism for heat, entropy and momentum. In this work the concern is mainly with the basic mechanism and the direction of movement of these cyclone waves.

5.1.3 Structure of the growing baroclinic wave

The motion must satisfy the constraints of the thermal wind and vorticity equation relationships as well as continuity. The standard vorticity equation may incorporate the equation of mass continuity to give what has been termed a "stretching equation".

$$\frac{D\zeta}{Dt} + \underset{\sim}{v}\beta = \frac{f}{\bar{\rho}} \frac{\partial}{\partial Z} (\rho w)$$

where ζ is relative vorticity

β is $\partial f/\partial y$

ρ is density of air

$\bar{\rho}$ is mean air density

v, w are conventional components of velocity $\underset{\sim}{V}$

$$\frac{D\zeta}{Dt} + \underset{\sim}{v}\beta \simeq f\frac{\partial w}{\partial Z} + \frac{fw}{\rho}\frac{\partial \rho}{\partial Z} \qquad \ldots\ 5(\text{vii})$$

(assuming $\bar{\rho} \simeq \rho$)

It may be readily observed that if v and w are positively correlated, then the second term on the right, the mass

Fig. 5.2 Growing Baroclinic Wave

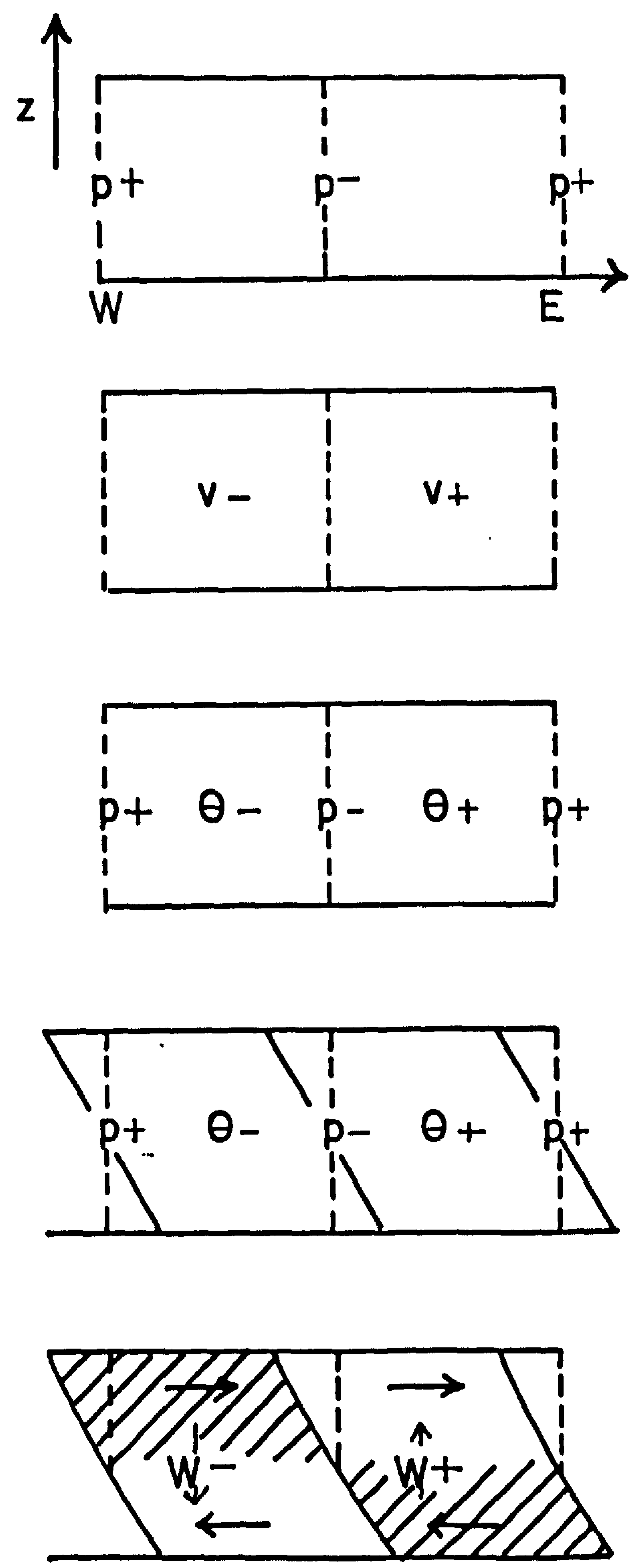


FIG 5.2 A SEQUENCE OF HEIGHT-LONGITUDE SECTIONS THROUGH A WAVE, SHOWING HOW GEOSTROPHIC, THERMAL WIND & VORTICITY EQUATIONS CAN BE SATISFIED SO LONG AS THE WAVE MOVES WITH THE MEAN ZONAL VELOCITY FOR THE LAYER.

divergence, enhances the β-effect. It is also seen that parcels of air must increase their spin cyclonically as vortex lines are stretched as shown by the term +'ve $\left(\frac{\partial w}{\partial Z}\right)$. If the trough line of a depression is vertical, as convergence occurs at the surface and near the tropopause, both regions experiencing stretching, then an equal and opposite squashing will occur at an intermediate level. The integrated vorticity generation through the trough over the height of the troposphere will be zero and no mechanism will exist to sustain positive relative vorticity. However, it may be observed that hydrostatic balance and the thermal wind equation require that the trough line should slope towards the west with increasing height, (pressure falling off more rapidly with height in the cold air to the rear of the cold front of a middle latitude wave). This slope is observed when overlaying successive constant pressure charts showing amplifying waves. The amount of slope indicates the rate at which an overall stretching is taking place and therefore the rate at which positive relative vorticity is being generated in the wave. The shaded section of Fig. 5.2 with canted trough indicates the zone of stretching $(+^{\partial w}/_{\partial Z})$ and change in vorticity $(^{D\zeta}/_{Dt})$.

This knowledge is a most important part of the procedure to be outlined in ship-based weather routeing. The Fig. 5.2 indicates the trough, defined as the lowest pressure indicator, necessarily inclined into the colder air aloft where θ- is situated.

5.2 Steering

5.2.1 The steering level

With the constraints placed to achieve a positive vorticity balance flow is shown "relative" to the wave itself. Thus the wave is moving faster than the air at low levels, so the relative motion of the air is east to west and the upper air is overtaking the waves experiencing westerly flow. It follows that at some intermediate level the wave and the flow have to move at the same velocity to be consistent with the constraints mentioned. This middle level flow is known as the steering level, wave celerity and air velocity in the waves are approximately equal so this should be the best level to observe the wave.

Ignoring the mass divergence term in equation 5(vii), the vorticity equation becomes

$$\frac{D\zeta}{Dt} = f\frac{\partial w}{\partial Z} - \underset{\sim}{v}\beta \qquad \ldots 5(\text{viii})$$

For wavelike motion, near the steering level where there is no zonal advection relative to the wave $\frac{D\zeta}{Dt}$ must be small relative to v and a balance must be maintained between vorticity changes due to meridional advection and the β effect, and those due to vortex stretching, i.e.

$$\underset{\sim}{v}\beta \simeq f\frac{\partial w}{\partial Z} \text{ at the steering level.}$$

If this steering level is near a lower boundary then as w=0 at the boundary then $\frac{\partial w}{\partial Z} > 0$ for v>0 at the steering level. Thus if $\frac{\partial w}{\partial Z}$ changes slowly in between, then w>0 for v>0 at the steering level, and a low level of steering implies therefore that $\overline{vw}>0$. This is consistent with actual conditions if the thermal wind is westerly. Whether this motion will be amplifying or diminishing depends on

5.3 Phase & amplitude variations in a developing cyclone wave

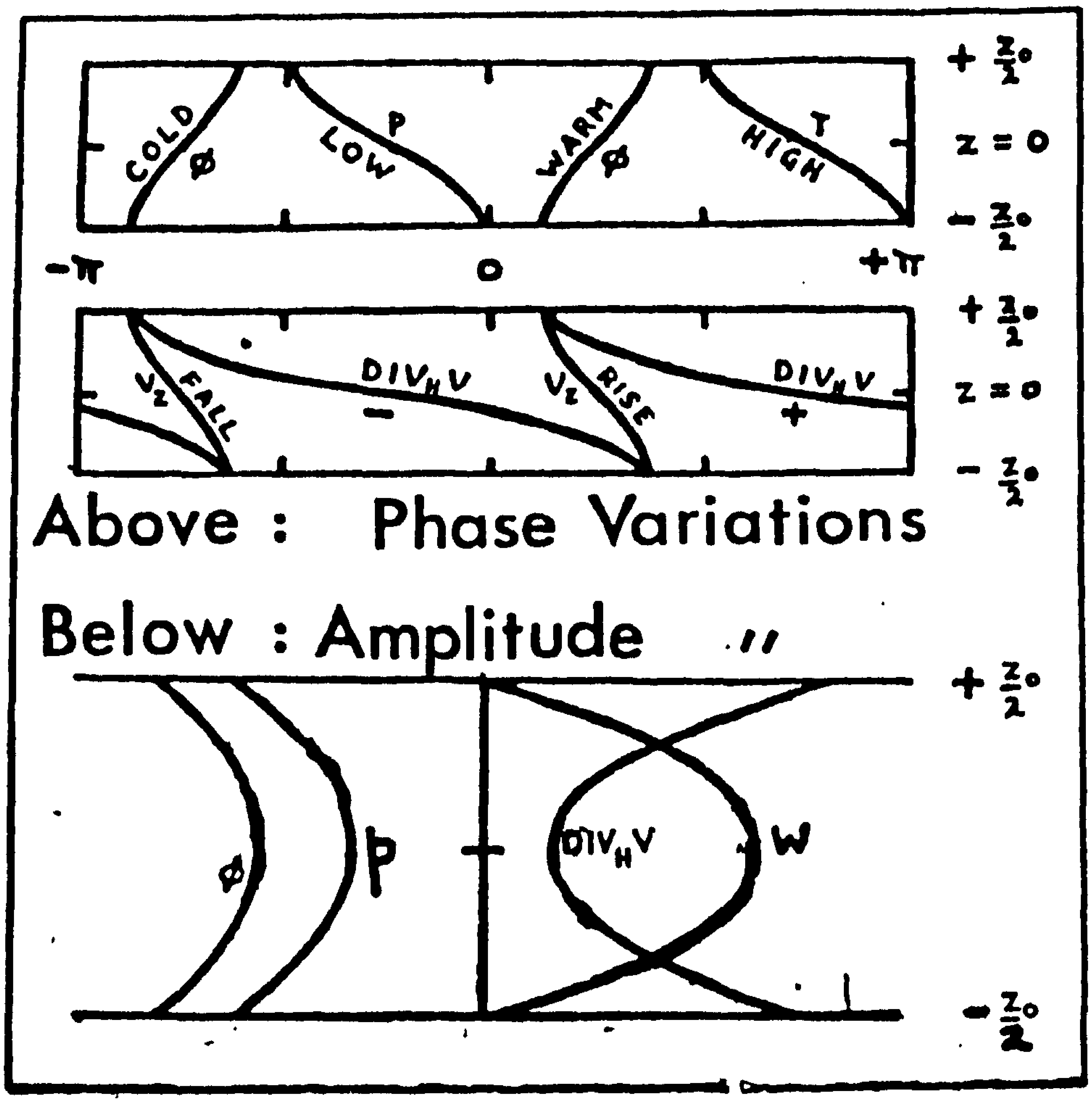


FIG. 5.3. Structure of developing cyclone wave, according to Eady (1949). The horizontal extent of the latitudinal vertical sections in the upper part of the diagram is a few thousand km, while the vertical extent is only about 10 km. The wave disturbance in a westerly current appears as a series of growing ridges and troughs of pressure (P) and tongues of cold and warm air (Ø), accompanied by regions of vertical velocity (W) and horizontal divergence (DIV$_H$ V). These features have axes which are aligned N-S, and slope in the E-W direction as shown in the upper part of the figure; the distribution with height of their intensity is shown in the lower part.

the phase difference between the velocity and temperature fields. Conversely an upper steering level implies $\overline{vw}<0$ which would not satisfy the prevailing westerly wind condition but would agree with an easterly regime. We can suppose the correlation between v and w and $\frac{\partial w}{\partial Z}$ are implied by the nature of the energy transformations and that the actual steering level will vary around some middle level.

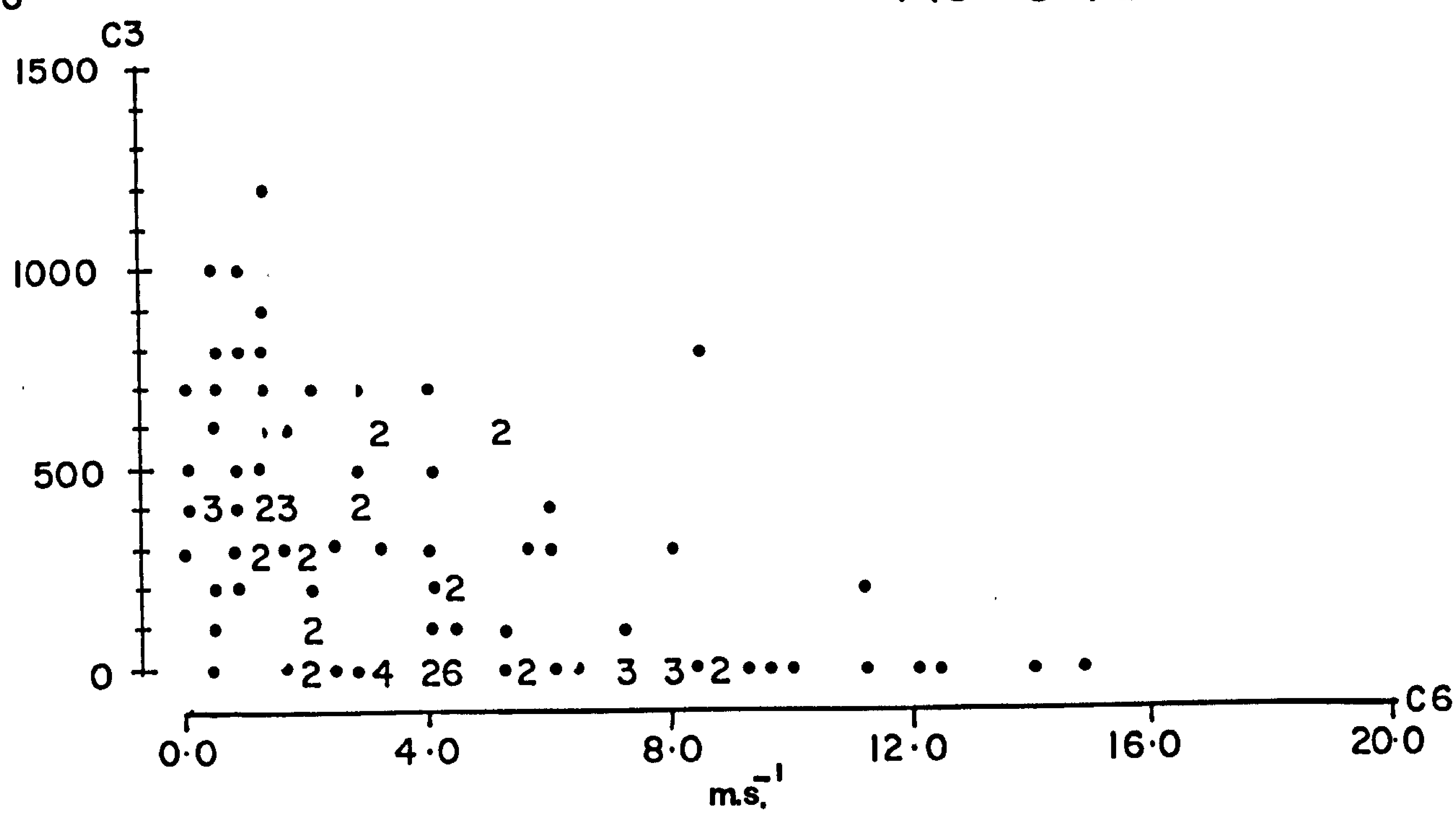
The tropopause in middle latitudes is typically situated at some 11 or 12km above the surface, the 500mb constant pressure surface at a mean height of 5.7km conveniently bisects the troposphere and may be taken to approximate a steering level. It therefore becomes appropriate to test the effectiveness of 500mb flow as an indicator of future movement of baroclinic waves. The theory, energetics and structure referred to indicates that this will only be effective whilst the trough line of the wave is canted to the west with height. Fortunately this event occurs whilst the depression is over the ocean, certainly on the western side and often for the complete ocean transit.

5.2.2 Steering of Depressions (case studies)

Twenty four depressions were observed as they traversed the North Atlantic Ocean and their tracks compared with appropriate 500mb charts. Fourteen separate depressions were identified and traced during January and February 1980 and a further ten during June and July 1980. Observations of the velocity of movement of the depression ($\underset{\sim}{V}s$) as indicated by successive surface analysis charts were catalogued together with the velocity of flow obtained from the meaned velocities in the vicinity of the trough line at 500mb.($\overline{U}_{500}$). This total flow as indicated by the

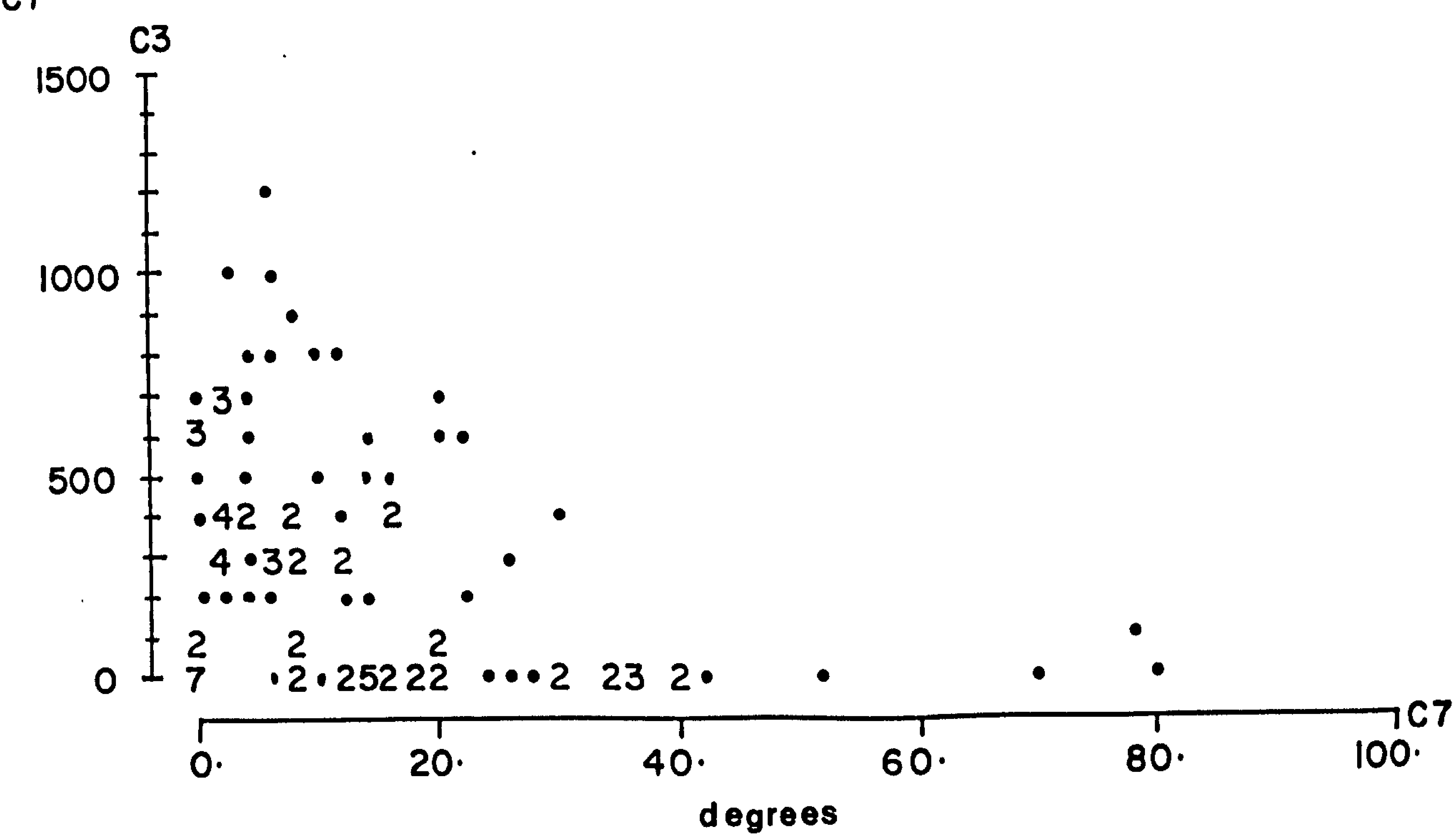
HEIGHT 12 km.
PLOT C3 C6

FIG· 5·4a



HEIGHT 12
PLOT C3 C7

FIG· 5·4b



streamline pattern was divided into its component velocities by calculating a mean 500mb ($\bar{U}_{500}$) value for each month from the mean meridional temperature gradient for the North Atlantic Ocean and adjacent coastlines across the baroclinic zone. This value was subtracted from the total value to give an estimated eddy component U'_{500}. Thus:-

$$U'_{500} = U_{500} - \bar{U}_{500}$$

The eddy component was then compared with the observed wave velocity and a residual obtained

$$\text{Residual} = \underset{\sim}{V}_s \sim U'_{500}$$

The "residual" was then compared to the cant or displacement of the trough line of each depression for each day of observation, as obtained by a comparison of surface and 500mb positions. As explained in the previous section, 5.2.1, a depression will be thermodynamically driven as long as the trough line retains appreciable cant to the west with height.

The data (Appendix 5) were analysed and an evident relationship established between the trough line cant and the "steering" as indicated by the 500mb flow.

A multiple regression analysis program was used to compare the "residual" with the trough line cant. Results are shown in the set of diagrams 5.4.

The results are most promising insofar as the 500mb streamlines give an excellent indication of depression paths, on the western side of the ocean. On the eastern side the indication of future movement is usually less accurate, as the trough line is now normally vertical or quasi-vertical. Blocking high pressure systems are also more prevalent on the eastern side of the ocean (see 5.2.4), disturbing the largely zonal characteristic of the trans-ocean passage. In undertaking this exercise certain observational difficulties became evident thus:-

In several cases a primary depression developed a secondary or wave depression which created a disturbance in the vertical energy balance; again this occurred largely on the eastern side of the ocean. On occasions it was difficult to establish an exact position of the trough line aloft, this difficulty was more evident at coastlines where the ocean/continent thermal contrast long wave component may mask the eddy value at 500mb.

This effect operates in phase in winter time and out of phase in summer to growing baroclinic waves moving off the eastern seaboard of the States.

In calculating 500mb velocity values using the constructed scale an estimated error of $\pm 3ms^{-1}$ was evident for high velocities ($50ms^{-1}$) and an estimated error of $\pm 0.3ms^{-1}$ for low velocities ($5ms^{-1}$) i.e. ± 6% error. Thus all of these collected data were subject to small transferred errors of compilation.

A measure of these errors is evident from the regression figures (Fig. 5.4). 400mb flow and 600mb flow were considered and examples taken for an indication of steering. In general the flow patterns are very little different from the general trend as indicated by the 500mb flow. For practical purposes it was considered necessary to discard these approaches as 500mb analysis and prognosis charts are readily available on marine facsimile transmissions but the adjacent levels are usually only available as an analysis chart, if at all.

<u>The regression programme for steering analysis</u>

The regression programme has a number of optional arguments. The basic regression is

REGRess y in C using K predictors in C, ..., C.

The command finds the least squares linear equation for predicting Y from K predictors X1, X2, ... Xk. This equation is of the form

$$Y = b0 + (b1)\ x\ 1 + (b2)\ x\ 2 + \ldots + (bk)\ xk.$$

The values b0, b1, bk are found by the Minitab programme and are called regression coefficients. By using Minitab functions such as SQRT, equations such as Y = b0 + (b1)X + (b2)X-squared, can be fitted, creating a column of X-squares. Analysis of variance and/or covariance can be done by creating the appropriate variables.

Regression outputs are thus obtained from the standard multiple regression programmes giving the regression equation which best fits the data according to the least squares criterion.

To obtain the mean velocity of the flow in the trough at 500mb, it was necessary to take several positions near and along the trough and measure a wide range of values to evaluate a speed. The direction was more readily obtainable from the general streamline direction ahead of the trough.

$\bar{U}$ was calculated as a mean for each month (not for each depression) for the whole of the ocean using meaned meridional temperature information in the thermal wind equation. Thus it was assumed, not only that this held for the whole month under observation but that it was characteristic of each meridian regardless of proximity of land mass. This may appear to be a cavalier assumption at first sight, however, because of the large number of values used, the $\bar{U}_{500}$ results appear to be realistic. Doubtless there exists a range of $\bar{U}_{500}$ trans-ocean but the monthly range is approximately an order of magnitude different from the calculated mean used, thus the method of monthly means for $\bar{U}_{500}$ is justified. Values of $\bar{U}_{500}$ as calculated: 14.5ms^{-1} for January, 15.1ms^{-1} for February and 8.2ms^{-1}, 7.8ms^{-1} for June and July respectively. (A variation of only one half of metre per second over a period of one month is evident from the calculations).

The velocities of the depressions were obtained by Traverse Table interpolation using standard nautical tables. Inevitably errors arise in assumed linear interpolation.

Positional information was obtained from the daily European Meteorological Bulletin chart on stereographic projection scale $1 : 3.10^7$. Latitude and Longitude was estimated from a devised scale for the charts. Velocities at 500mb were calculated using a Geostropic wind scale constructed for the scale of the Bulletin. Readings were meaned along the trough.

The R-squared output indicates a measure of how well the regression equation fits the data, with 100% indicating a perfect fit. Defined by 100 (SS due to regression)(SS total). It is also equal to the correlation between the observed and predicted values.

$$R^2 = \frac{100\ (\text{SS regression})}{\text{SS total}}$$

The programme identified the following parameters

C1 = Surface speed (Vss)

C2 = Surface direction (Vsd)

C3 = Cant of trough line

C4 = U'_{500} speed (U'_{500s})

C5 = U'_{500} direction (U'_{500d})

C6 = C1 - C4

C7 = C2 - C5

C8 = 1 January

2 February

3 June

4 July

Speed

A regression of C3 against C6 resulted in the regression equation

$$Y = 437. - 42.8 \times 1$$

with an R^2 value of 25.2%

Direction

Whilst a regression of C3 against C7 resulted in the equation

$$Y = 451. - 35.9 \times 1 - 3.04 \times 2$$

with an R^2 value of 27.2%

The linear regression as a statistical exercise was inconclusive because of the low R^2 value obtained.

However it may be readily observed from the diagram 5.4 that small residuals were experienced in both regression exercises in the majority of cases as long as a trough line cant of 400km or more was observed.

In the case of the speed exercise the residual was only measured in excess of $4ms^{-1}$ on one occasion. The direction of flow residual was a maximum of $\pm 20^0$ for all cases with a trough line cant in excess of 400km, a rounded residual value of $\pm 10^0$ was the norm.

The exercise was repeated for the linear regression on a monthly basis. Further analysis involved regression to both exponential ($\log_e$) and standard logarithmic ($\log_{10}$) forms for monthly blocks of discrete data in addition to the total data. The results are contained in the table 5.1. In all cases a relatively low "R^2" value resulted (apart from the July analysis, where the smallest data population was used).

It is evident that each case could be described by very different polynomial expressions and that no generalised equation could be used to relate the trough line cant to the Residual*. It should

\(Unlike the regression undertaken in 3.3.2 for the production of ship performance curves using multiple regression techniques to produce polynomial equations, the variation in physical structure throughout the life of a depression coupled with the relatively low data amount, invalidates such a development).

also be stated that the number of statistical values necessarily used for the monthly analyses was thought to be rather low which must also contribute to the differing regression factors obtained from the monthly analysis. However the work has shown that depressions are steered by the 500mb flow whilst in their growing stage, i.e. when the trough line is canted appreciably to the west with height (>400km displacement between sea level and 500mb). This invariably occurs on the western side of the Ocean, i.e. west of 30^{o}W meridian.

Table 5.1

ANALYSIS OF MLR of CANT against RESIDUAL ($\chi_s \sim U_{500}$)

FORM OF EQUATION

1. Linear $\quad Y = a + m_1X_1 + m_2X_2 + \varepsilon$

2. Standard logarithmic $\quad \text{Log } Y = \log a + m_1\log X_1 + m_2\log X_2 + \log \varepsilon$

3. Exponential $\quad \text{Log}_e Y = \log_e a + m_1\log_e X_1 + m_2\log_e X_2 + \log_e \varepsilon$

Form of equation	a	m_1	m_2	R^2	number of obs.
Total					
2. Standard log	2.21	-1.29	-0.147	28.6	106
3. Exponential	5.09	-1.29	-0.147	28.6	106
BY MONTH Jan					
1. Linear	521	-54.5	-1.56	27.3	33
2. St. log	2.02	-1.83	0.162	30.5	33
3. Exponential	4.66	-1.83	0.162	30.5	33
Feb					
1. Linear	464	-25.2	-5.53	26.9	28
2. St. log	2.24	-1.29	-0.187	29.4	28
3. Exponential	5.15	-1.29	-0.187	29.4	28
June					
1. Linear	426	-42.3	9.49	20.2	23
2. St. log	2.31	-1.89	0.648	16.0	23
3. Exponential	5.31	-1.89	0.648	16.0	23
July					
1. Linear	393	-31.7	-10.9	50.0	22
2. St. log	2.76	-0.522	-1.4	51.3	22
3. Exponential	6.35	-0.522	-1.4	51.3	22

Note:(1) 1 was added to all zero values for Log and Log_e values.

5.2.3 <u>Frictional run down of the wave</u>

As the trough line of the wave becomes vertical so the positive relative vorticity generating forces disappear and the depression will be dissipated by frictional forces. Thus ignoring the advection terms and assuming steady state, the horizontal components of the momentum equation may be cross differentiated for curl $\underset{\sim}{V}$. Ignoring the β effect. T is shearing stress.

$$f \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial x}\left(\frac{\partial T_y}{\partial Z}\right) + \frac{\partial}{\partial x}\left(\frac{\partial p}{\partial y}\right) - \left(- f \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial y}\left(\frac{\partial T_x}{\partial y}\right) + \frac{\partial}{\partial y}\left(\frac{\partial p}{\partial x}\right)\right) = 0$$

$$\frac{\partial}{\partial Z}\left(\frac{\partial T_y}{\partial x} - \frac{\partial T_x}{\partial y}\right) = - f \left(\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v)\right)$$

By continuity of momentum $\frac{D}{Dt}(\rho \underset{\sim}{V}) = \dot{0}$ and ignoring sound waves $\frac{\partial \rho}{\partial t}$

$$\frac{\partial}{\partial Z}\left(\frac{\partial T_y}{\partial x} - \frac{\partial T_x}{\partial y}\right) = + f \frac{\partial}{\partial Z}(\rho w) \qquad \text{... 5(ix)}$$

The stress torque is thus equated to a "squashing" term, and integrating from Z_0 to the top of the atmospheric boundary layer where T the stress is zero then

$$(\rho w)Z = \frac{1}{f}\left(\frac{\partial T_y}{\partial x} - \frac{\partial T_x}{\partial y}\right) \qquad \text{... 5(x)}$$

Vertical velocities are induced at the top of the boundary layer, assuming surface stress has a non-zero torque. Near latitude 30^o, u and $\therefore$ T_x increases with latitude, whilst T_y is small as is v. $\partial T_x/\partial y$ is positive, hence (ρw) is negative, and a

"-w" with friction as an independent mechanism.

τ is a function of ρ, $\frac{\partial u}{\partial Z}$, Z.

Let $\tau = k\rho u$ (k is a constant evaluated empirically at $\simeq 1.0\text{-}1.5 cms^{-1}$ depending on u) GREEN (41).

Substituting in equation 5(vii) and ignoring the β effect

$$\frac{D\zeta}{Dt} = \frac{f}{\bar{\rho}}\frac{\partial}{\partial Z}(\rho w) = \frac{f}{\bar{\rho}}\frac{\partial}{\partial Z}\frac{1}{f}\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right) =$$

$$\frac{f}{\bar{\rho}}\frac{\partial}{\partial Z}\frac{1}{f}\left(\frac{\partial}{\partial x}(\rho k v) - \frac{\partial}{\partial y}(\rho k u)\right)$$

$$\therefore \frac{D\zeta}{Dt} = \frac{f}{\bar{\rho}}\frac{1}{f}\frac{k\rho}{H}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) = +\frac{\rho k \zeta}{\bar{\rho} H}$$

$$\text{as } \frac{D\zeta/Dt}{\zeta} = \frac{k}{H}\frac{\rho}{\bar{\rho}} \quad \text{where H is height of system} \simeq 10\text{km}$$

and integrating

$$\text{Log}_e\ \zeta = -k\frac{\rho}{\bar{\rho}}\left(\frac{t}{H}\right)_0^{t^1}$$

or

$$\zeta\ \text{parcel} = \zeta_0 \exp\left(\frac{-k\rho t}{\bar{\rho}\ H}\right) \qquad \ldots 5(xi)$$

Let $\rho = 1.3 kg\ m^{-3}$

$\bar{\rho} = 0.7 kg\ m^{-3}$

$k = 1.5 cm\ s^{-1}$

t is therefore directly proportional to $\frac{\bar{\rho}H}{\rho k}$, the time scale for a cyclone to die down to $\simeq \frac{1}{e}$th of its value

$\frac{10^6}{1 \times 2.7}$ secs or 4 days

The energy spectrum of a depression would therefore show a two or three-day build-up derived from baroclinic instability associated with a canted trough line and a four day or so decay as the trough line becomes vertical and the system thermodynamically unbalanced. It is important to note that the growing phase occurs largely over the ocean.

5.2.4 <u>The Middle Tropospheric flow field of middle-latitudes</u>

The general westerly flow as observed in middle latitudes may be considered to be made up of the mean component ($\bar{u}$) and eddy component (u').

$$u = \bar{u} + u' \qquad \text{... 5(xii)}$$

The mean westerly flow is generated by the mean meridional temperature gradient as shown by the Thermal wind equation:-

$$\bar{u}_T = \frac{g}{f\bar{T}} \frac{dT}{dy} \qquad \text{... 5(xiii)}$$

The mean flow thus generated is perturbed by the permanent effect of topography, and the seasonal effects of ocean-continent thermal contrasts. These effects lead to characteristic standing waves which are well understood and documented HOLTON (*48*), HESS (*45*).

Further localised blocking of the westerly flow complicates and clouds the issue by the occasional interference of "rogue" warm blocking anticyclones. The mechanism of these has been described by GREEN (*41*), and attributed largely to lower-stratospheric cooling. DAVIES (*24*), recognises the difficulty in predicting these climatic anomalies. He suggests that the problem will only be solved by an analysis involving interactions between global scale energy changes and continental scale systems. But the ever increasing resolution of numerical models, necessary for this exercise brings with it a growth of grid point numerical errors which in turn may preclude further substantial advance in solving the problem. However, in a later paper DAVIES (*25*), states that more recent developments in understanding large scale persistent flow types and associated, enlightened data analyses are leading to his conversion from "a position of quasi-scepticism to one of accepting that the development of a really useful seasonal forecasting system is a strong possibility".

J.F. AUSTIN (*40*), suggests that the splitting of westerly winds by blocking anticyclones is initially due to simple interference between stationary planetary waves with very large amplitudes but normal phases. A slowly moving long wave (dominated by the Rossby retardation; a wave persistent if the wavelength L is related to the mean zonal wind ($\bar{u}$) and the β effect by

$$L^2 = \frac{4\pi\bar{u}}{\beta} \qquad \ldots\ 5(\text{xiv})$$

causes a split in the jet. Further eddy activity in the baroclinic zone pumps anticyclonic vorticity into the region between the jets, particularly at upper levels. Descent subsequently transfers vorticity to the lower levels to be removed by surface friction, maintaining a steady circulation. Thus the blocking anticyclones and the vital tropospheric warming to establish them may be considered to be dynamically driven by the action of the eddies. The blocking anticyclone is usually recognised as having a persistence substantially longer than three days so that they are distinguished from the ridges accompanying the usual transient troughs. Significant to this thesis AUSTIN (*40*), has recognised two preferred locations for blocking anticyclones in the northern hemisphere, namely the NE Atlantic and NE Pacific; with nearly twice as many cases of blocking occurring in the former than the latter. The case studies of Austin's work showed that on average 30% of the days in any one month are blocked in the Atlantic sector, most likely to occur on the coast of Europe, or in mid-Atlantic in winter but over western Europe in summer.

Blocking never commences with the amplification of a single wave number in isolation but with a local reinforcement of long waves at the 500mb level. In the Atlantic the reinforcement is either between wave numbers one and two or between wave numbers two and three.

Blocking only occurs in general circulation models which include mountains and allow for land-sea distributions. Such models therefore contain planetary waves due to the forcing, and baroclinic waves due to the instability associated with the pole-equator temperature gradient. An interaction between these two types of wave could be responsible for maintaining blocking.

The significance of these interactions illustrates the difficulties that this presents in the forecasting of the flow field to indicate future blocking. The 500mb forecast charts may, on occasions of blocking, not truly reflect or incorporate the contribution of these systems. Thus although the standing waves produced by the dual effects of topography and land-sea thermal gradients and the transient effects of baroclinic waves can be established and accurately reproduced, the consequent interactions and feedbacks are not as yet fully understood. Nevertheless, the mid-tropospheric flow patterns as analysed, together with the subsequent prognosis, represent the best available indicator of movement of transient weather systems and therefore provide a useful tool for the ship master in planning his voyage. Optimistically a more detailed method of detecting and forecasting future blocking, together with a measure of persistence, will be forthcoming. Cases such as the three-month block in the eastern North Atlantic, which occurred from January to March inclusive in 1963, may be used to benefit the seafarer in planning his voyage MOTTE (77). In general it was shown that the great circle route or a more northerly track would have been beneficial throughout the period for west-bound passages. This directly contravenes the usual practice of proceeding on a more southerly route trans-Atlantic in winter.

6. ROUTEING MODELS

6. ROUTEING MODELS

6.1 Navigation

6.1.1 The Stereographic projection

The Stereographic projection is commonly used as a framework for areal representation of meteorological data. Almost all of the charts available from marine facsimile transmissions are of this form.

In Figure 6.1(A) and (B) the earth's surface is mapped onto a plane, by projecting positions on the earth's surface from the point S through the position P to P' on the plane.

Note in Figure 6.1 α is the co-latitude

$$r = 2R \tan \frac{\alpha}{2} \qquad \ldots 6(i)$$

For Longitude scale

$$\frac{\text{Length of a parallel on graticule}}{\text{Length of a parallel on earth}} = \frac{2\pi r}{\text{parallel of latitude}}$$

$$= \frac{2\pi . 2R \tan \alpha/2}{2\pi . R \sin \alpha} = 2 \frac{\sin \alpha/2}{\cos \alpha/2} \cdot \frac{1}{2 \sin \alpha/2 \cos \alpha/2}$$

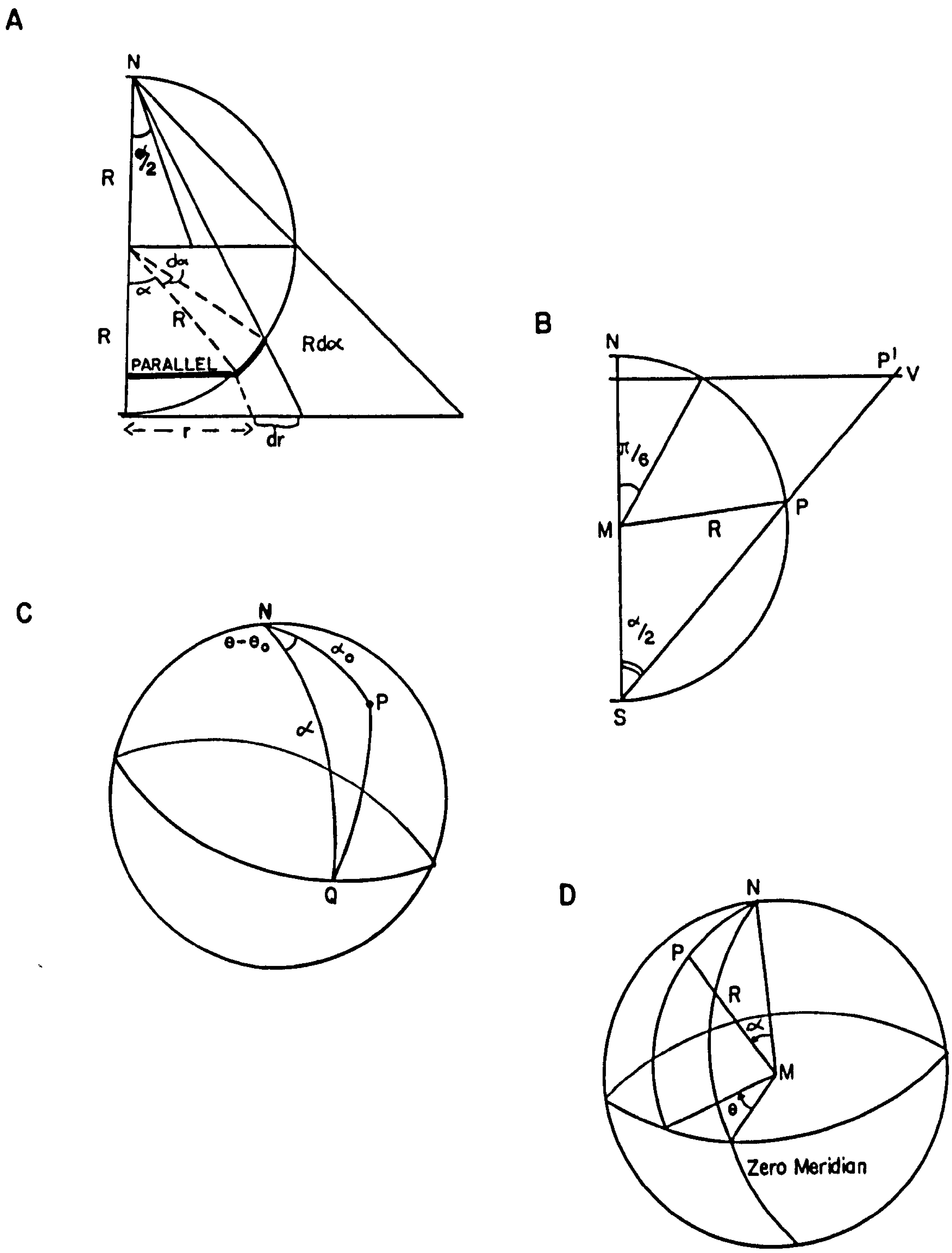
$$= \text{Sec}^2 \alpha/2 \qquad \ldots 6(ii)$$

For latitude scale: If α is increased by $d\alpha$, r is increased by dr, and corresponding length on earth is $Rd\alpha$

$$\text{Scale} = dr/Rd\alpha = \frac{2R}{R} \frac{1}{2} \sec^2 \frac{\alpha}{2} = \sec^2 \frac{\alpha}{2} \qquad \ldots 6(iii)$$

as 6(ii) = 6(iii) the projection is orthomorphic, facilitating directional presentation, but presenting difficulties in representation of distance with an irregular non-linear interpolation because of the $\sec^2 \alpha/2$ variation. It is relatively easy however to construct a variable distance scale to use

FIG. 6.1


A
N
R
α/2
dα
α
R
R
Rdα
PARALLEL
r
dr
B
N
P'
V
π/6
M
R
P
α/2
S
C
N
θ-θ₀
α₀
P
α
Q
D
N
P
R
α
M
θ
Zero Meridian

with these charts.

S.J. BIJLSMA (9), has shown using polar co-ordinates r and θ that:

$$r = \frac{R}{s}(1 + \cos \pi/6) \tan \frac{\alpha}{2} \quad \text{where s is a scale factor}$$

Considering an orthogonal co-ordinate system with co-ordinates X_1 and X_2, the relation between polar and rectangular co-ordinates is given by

$$X_1 = X_{1n} + \frac{r}{d_o} \sin\left(\theta - \frac{\pi}{6}\right)$$

$$X_2 = X_{2n} + \frac{r}{d_o} \cos\left(\theta - \frac{\pi}{6}\right) \qquad \ldots 6(iv)$$

X_{1n} and X_{2n} are the co-ordinates of the projected north pole, d_o the grid mesh distance. From 6(iv) the inverse transformation evolves

$$\theta = \arctan\left((X_1 - X_{1n})/(X_2 - X_{2n})\right) + \frac{\pi}{6} \qquad \ldots 6(v)$$

$$\alpha = 2 \arctan\left(a_o \sqrt{(X_1 - X_{1n})^2 + (X_2 - X_{2n})^2}\right)$$

with

$$= \frac{s\, d_o}{R(1 + \cos \pi/6)}$$

By differentiating 6(iv) the local transformation is obtained

$$dX_1 = m(\alpha)\, R\left(\sin\left(\theta - \frac{\pi}{6}\right) d\alpha + \cos\left(\theta - \frac{\pi}{6}\right) \sin \alpha\, d\theta\right)$$

$$dX_2 = m(\alpha)\, R\left(\cos\left(\theta - \frac{\pi}{6}\right) d\alpha + \sin\left(\theta - \frac{\pi}{6}\right) \sin \alpha\, d\theta\right)$$

with

$$m(\alpha) = \frac{1 + \cos \pi/6}{s\, d_o(1 + \cos \alpha)}$$

Such that differential distances on the earth's surface must be multiplied by the map factor $m(\alpha)$ in order to convert them into distances in the $(X_1\ X_2)$ plane.

For the purposes of navigation, sailings are usually referred to great circle or rhumb line courses. Any computations should include the special requirements of these sailings.

6.1.2 Great circles and Rhumb lines

(i) Great circles

In the Figure 6.1(C) with spherical co-ordinates (θ_o and α_o) from the spherical triangle NPQ

$$\cos(\theta - \theta_0) = -(\tan\alpha \tan\alpha_0)^{-1} \qquad \ldots\ 6(vi)$$

Combinations of this equation with 6(v) gives the equation of the projection of the great circle in the (X_1, X_2) plane, again a great circle with

$$(X_1 - X_{1m})^2 + (X_2 - X_{2m})^2 = s_o^{\,2}$$

so,

$$X_{1m} = X_{1n} + s_o \sin\alpha_o \sin(\theta_o - \tfrac{\pi}{6}),$$

and

$$X_{2m} = X_{2n} + s_o \sin\alpha_o \cos(\theta_o - \tfrac{\pi}{6})$$

$$\text{and } s_o = (a_o \cos\alpha_o)^{-1}$$

So the spherical co-ordinates θ_o and α_o are obtained by substituting the co-ordinates of two points of the great circle in 6(vi).

(ii) Rhumb lines

With conformal mapping, a rhumb line is charted as a logarithmic spiral hence:-

$$r = r_1 \exp(k(\theta-\theta_1)) \qquad \ldots 6(vii)$$

$$k = \ln({}^{r}2/{}^{r}1)/(\theta_2-\theta_1) \text{ and}$$

$$r_i = \frac{R}{s}\left(1 + \cos\frac{\pi}{6}\right) \tan \alpha_{i/2} \; (i = 1,2),$$

where (α_1, θ_1) and (α_2, θ_2) are the co-ordinates of two points of the rhumb line.

6.1.3 Computer generated routes

Before the navigational steps can be taken it is necessary to store in some detail the required environmental data. This may be considered as both short term and long term data. Thus sea state information, which is readily available (usually from conversions of surface meteorological data, as explained in Chapter 2) for up to 72 hours, is the data used to generate courses and time fronts for two days ahead, i.e. a short term contingency. Long term data may be used from several sources and representing several approaches to the overall problem of routeing a vessel trans-ocean. Thus,

(i) Analogue wave data from 3/4 to 10 days ahead
(ii) Fog data from climatological charts
(iii) Wind data from climatological charts
(iv) 500mb flow from mean monthly charts

These chosen data are stored and readily available from random access files by sub-routines to convert polar positions to grid co-ordinates and then interpolate for time and space to reflect the likely environmental conditions along several routes.

Ship performance data, in one of the several presentations explained in Chapter 3, is also stored and indexed. Thus the ship's expected speed of advance along any planned course can be estimated by an environment/ship performance data comparison.

Thus computer generated routes from departure port to destination are possible. KLAPP, A.J. (56), has explained the grid arrays necessary to compute optimum courses as used at the American Fleet Numerical Weather Centre (FNWC). Basically there are two types of grid in use. A fixed grid, which does not allow for variations in ship's movement along the track and a variable grid, where the start of the grid is the present position of the vessel as the grid, in this case, is recomputed after each run.

When several ships are to be routed, as by a shore agency, the use of a computer is vital in both storing data and verifying routes.

6.1.4 Radials and Time Fronts

As seen from 6.1.2 radials or alternative courses drawn on a polar stereographic projection do not accurately lie along great circles, they do approximate more nearly to a great circle section than a rhumb line. For practical purposes where a relative difference between radials is required this inaccuracy is insignificant.

The practical mechanics of obtaining time fronts or loci from the positioning of radials has been explained in some detail by the author in a previous publication (77). Briefly, a transparent overlay is placed over the wave analysis and the wave height and aspect are used as variables to obtain relative speeds from ship performance curves (Chapter 3) for adjacent radials or courses some 10^o of arc removed from a comparison course. (Usually the great circle). From the ends of these vectors the process is repeated for a second period using the appropriate wave forecast chart.

Many papers have been produced during the seventies explaining various sophisticated models to adopt the above procedure to a computer exercise, the most recent and impressive of these by E. FRANKEL and H. CHEN (*36*), S.J. BIJLSMA (*9*), A.J. KLAPP (*56*).

Radials and Loci are computer generated. Environmental parameters are selected relative to the established ship position (usually on a grid co-ordinate system) and the ship's speed of advance is controlled by a speed profile relative to the environmental parameters (usually wave height is the predominant environmental argument).

The equations of motion of a ship in a Cartesian Co-ordinate System with co-ordinate X_1 and X_2 are given by

$$\frac{d\,X_1}{dt} = V\,(t, X_1, X_2, p)\cos p + s_1\,(t, X_1, X_2)$$

$$\frac{d\,X_2}{dt} = V\,(t, X_1, X_2, p)\sin p + s_2\,(t, X_1, X_2) \qquad \ldots\ 6(\text{viii})$$

V is the maximum attainable speed on course p between position co-ordinates X_1, X_2. The s functions denote velocity components of the ocean currents. This latter is an optional addition.

The path of the ship is determined continuously by values of

X_1 and X_2 updated with contiguous wave data on several adjacent courses.

6.2 Shore-Based Routeing Models

6.2.1 Optimal Control Theory

A preponderance of time and effort has been directed, since the advent of weather routeing, on various models to calculate a least time or optimum route, based on mathematical optimal control theory.

Consider a class of arcs

$$x_i(t) \qquad (i = 1, \ldots, n),$$

connected by differential equations

$$\frac{dx_i}{dt} = f_i\,(t,x,u) \qquad \ldots 6(ix)$$

$$(u = u_i, \ldots, u_p;$$
$$x = x_i, \ldots, x_n)$$

With end conditions

$$x_i\,(t_o) = x_{i_o},\; x_i\,(t_1) = x_{i_1} \qquad \ldots 6(x)$$

We now seek a set of functions u(t) and x(t) which minimises an integral of the form

$$I = \int_{t_o}^{t_1} f_o\,(t,x,u)\,dt$$

This problem has been identified as the control problem of BOLZA (*11*). BIJLSMA (*9*), distinguishes two cases, an unrestricted case, where no conditions are imposed and a restricted case, where the navigation area for that ship is bounded, say by ice or fog limits, or that certain courses are forbidden.

PAGE NUMBERING AS ORIGINAL

The integrals so produced for x and u render the distance and velocity terms along chosen radials. The actual control theory from the 1909 publication of Bolza has been further developed particularly by PONTRYAGIN (*85*), and later HESTENES (*46*), in a theoretical form with practical application to shore based routeing at de Bilt, Netherlands, by C. De WIT (*27*), and BIJLSMA (*9*), further applications have been made in the United States particularly at the Fleet Numerical Weather Centre of the United States Navy with commercial application by OCEAN ROUTES of California (*82*). The publications are voluminous and detailed and it is certainly not intended in this thesis to fully catalogue this work, merely to express a degree of understanding with a view to deciding the relevance to a ship-based operation.

6.2.2 Computation of the least time route

Emphasis has been placed, in the past, on achieving an optimum route which minimises ship transit time, that is

$$p(t) \quad = \quad 0 \leq t \leq t_i,$$

Subject to equation 6(viii) in Section 6.1.4 and introducing continuously differentiable multipliers $\lambda(t)$
where

$$\lambda(t) \quad = \quad (\lambda_0(t), \ldots, \lambda n(t)),$$
$$\lambda_0(t) \quad = \quad \text{constant} \leqslant 0$$

See HESTENES (*46*).

Vectors components $V_1 = V \cos p$ and $V_2 = V \sin p$ are obtainable from the equations

$$\frac{d\lambda_1}{dt} = -\sum_{i=1}^{2} \lambda_i \left(V_{ix_1} + S_{1x_1}\right) \qquad \ldots\ 6(xi)$$

$$\frac{d\lambda_2}{dt} = -\sum_{i=1}^{2} \lambda_i \left(V_{ix_2} + S_{ix_2}\right) \qquad \ldots\ 6(xii)$$

$$\sum_{i=1}^{2} \lambda_i V_{ip} = 0. \qquad \ldots\ 6(xiii)$$

It follows that along an extremal

$$\sum_{i=1}^{2} \lambda_i \left(V_i + S_i\right) = -\lambda_0 > 0 \qquad \ldots\ 6(xiv)$$

In the case of an optimal transit time t_i, where the time interval is to be reduced to a minimum, the least summation of the differentiable multiplier λ_i is sought and differential changes in the co-ordinates of the end point of radials are connected by the relation

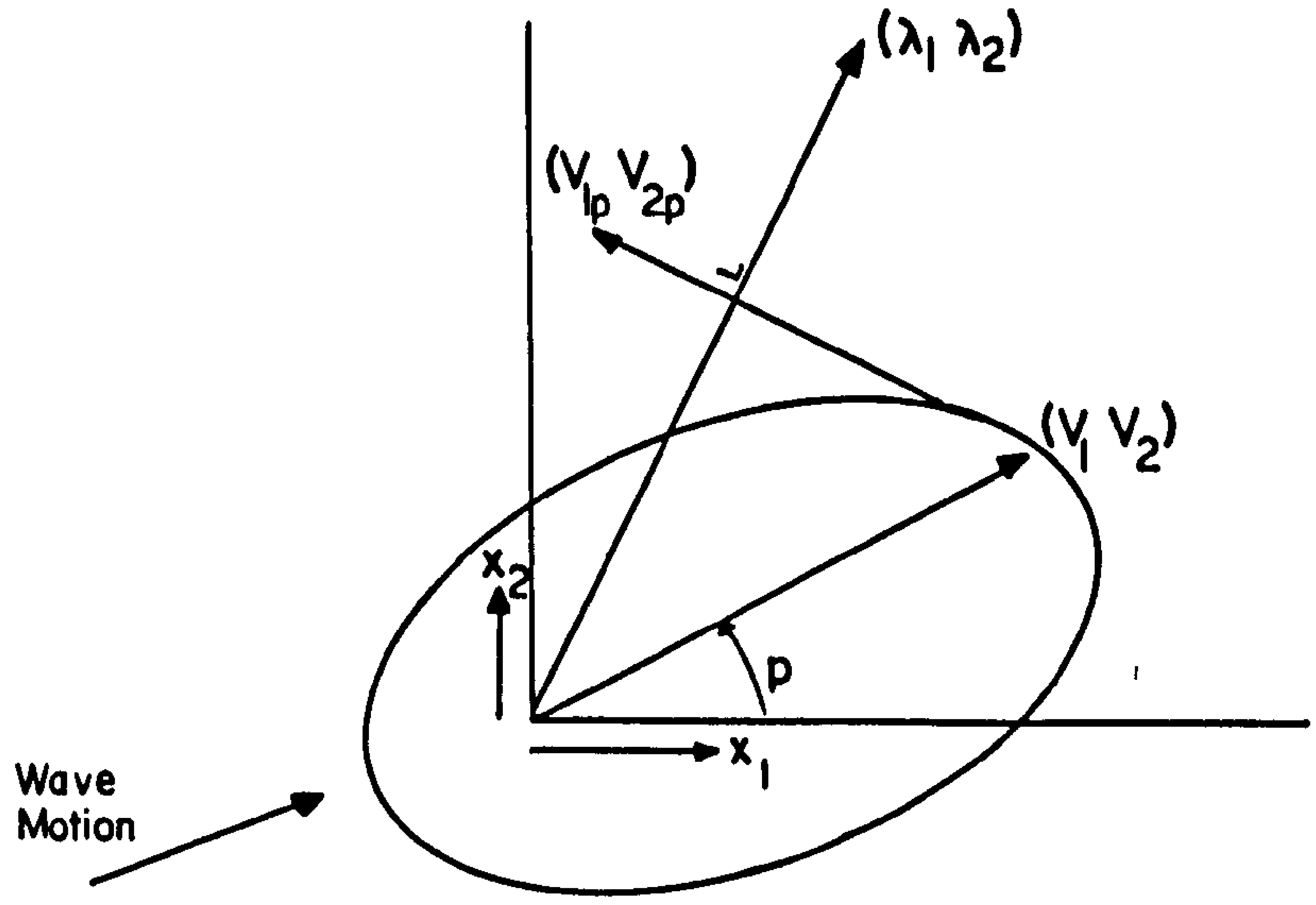
$$\sum_{i=1}^{2} \lambda_i(t_1)\, dx_{i1} = 0 \qquad \ldots\ 6(xv)$$

The actual velocity terms may be found by a continuous interrogation of stored performance data for a particular vessel, resulting in a ship's velocity (V) derived as a function of the angle between the ship's heading and the wave direction (see Fig. 2.2 wave spectra fields) for fixed values of x_1, x_2 and t.

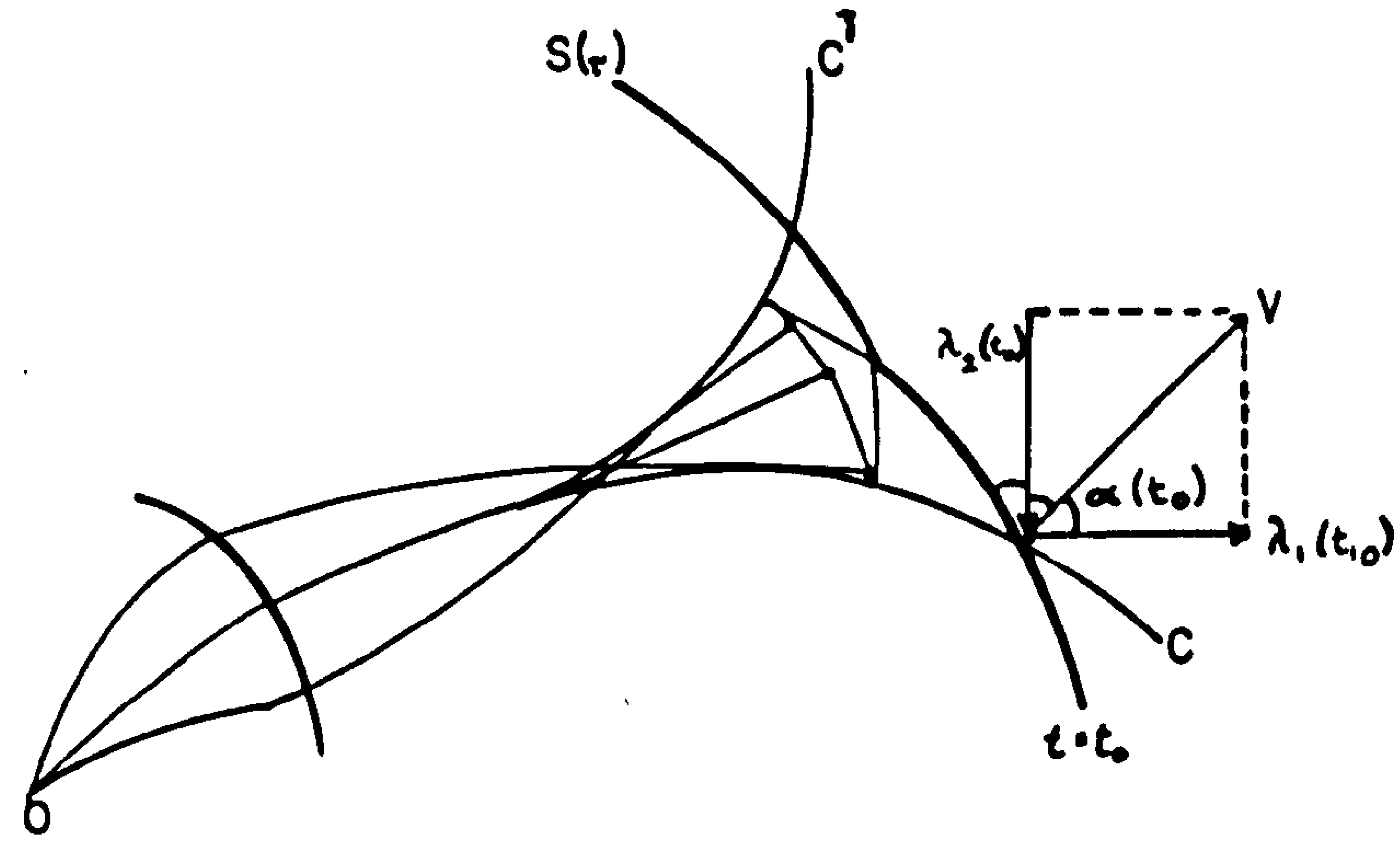
From equation 6(xiii), as illustrated in the Fig. 6.2 after S.J. BIJLSMA (*9*), instead of considering p as a function of the time t, it is regarded as a function of the variables x_1, x_2, λ_1, λ_2 and t. Equation 6(xiii) may then be written in the form

$$p = \arctan\left(\frac{\lambda_2}{\lambda_1}\right) + \arctan\left(\frac{V_p}{V}\right)$$

FIG 6.2



IN VIEW OF THE LEGENDRE CONDITION THERE IS A UNIQUE CHOICE FOR p.
THE COURSE p IS MEASURED AS INDICATED.



$S(\tau)$, THE SET OF ULTIMATELY DEFINABLE POINTS AT TIME $t=\tau$ FOR A SHIP STARTING AT TIME $t=0$ AT O, IS INDICATED BY A HEAVY LINE.

We are interested in continuous functions

$$p\ (t,\ x_1,\ x_2,\ \lambda_1,\ \lambda_2)$$

hence from equation 6(xiii)

$$\sum_{i=1}^{2} \lambda_i\ V_{ipp} \neq 0 \qquad \ldots\ 6(\text{xvi})$$

and in view of the Legendre Condition there is a unique choice for p as indicated in the Figure 6.2.

Combination of equation 6(xiii) and 6(xvi) gives

$$V^2 + 2V^2_p - VV_{pp} \neq 0 \qquad \ldots\ 6(\text{xvii})$$

Thus a numerical method for the computation of a least time track by a forward moving set of time vectors, the limits for a time period t of which are joined by a time front (S_T).

The set of equations 6(xi) - (xvii) containing functions, V and S, which are continuous for $0 \leqslant t \leqslant t_1$ and are continuously differentiable with respect to t. Thus integrating the system of equations we derive after a time τ a set of points $S(\tau)$, designated a time front.

Practical difficulties are met when constructing radials at the intersection of limits of radials emanating from differing points on a preceding time front. The intersections may be considered to fall between curves C and C^1 as shown and a relative minimum obtained. A non-singular extremal between two points cannot be a minimal curve if a conjugate point is contained between the two limits (the necessary condition of Jacobi). An arc satisfying the minimum conditions furnishes a relative minimum. An extremal

x_1 (t) (i = 1, 2) gives an absolute minimum if $x_i(T)$ (i = 1, 2) belongs to the boundary S (T) for all T with $0 \leqslant T \leqslant t_1$. Proved by HALKIN (43).

In solving the set of equations above, the time step is determined by the 12-hour availability of wave charts, although an assumed linear interpolation can give 6-hour time steps. In this example the relation between ship's velocity and wave direction/height is assumed to be of elliptic form (after S.J. BIJLSMA (9)), whilst derivatives are approximated to grid points (i,j) in the x_1 and x_2 directions. Thus the ship's speed is linearly adjusted to grid point i, j by

$$\left.\begin{aligned} Vx_1\ (i,j) &= \tfrac{1}{2}\,(V(i+1,\ j) - V(i-1,\ j)) \\ Vx_2\ (i,j) &= \tfrac{1}{2}\,(V(i,\ j+1) - V(i,\ j-1)) \end{aligned}\right\} \quad \ldots\ 6(\text{xviii})$$

Given that wave height and direction is known at each grid point, by application of the ship performance data (in the form of a polar velocity diagram in the case of de Bilt) the maximum distance that a ship can cover during a time step Δt is calculated for several directions from time $t = t_0$. We already know λ_1 $(t_0 - \Delta t)$, λ_2 $(t_0 - \Delta t)$, p $(t_0 - \Delta t)$ for the preceding time step along the extremal under consideration. (Except of course at the time t = 0, i.e. at the outset of the voyage, when the extremal commenced λ_1 (0) = cos α , λ_2 (0) = sin α which gave rise to the initial course p(0)).

We note that V_1 $(i_0,\ j_0)$ Δt, is equal to V $(t_0,\ i_0,\ j_0,\ p(t_0 - \Delta t))$ cos (p $(t_0 - \Delta t)$) Δt, is the distance that the vessel can cover in the x_1 direction, during the time step Δt, at grid point

(i_o, j_o). It follows that the corresponding distance in the x_2 direction is given by

$$V_2 (i_o\ j_o)\ \Delta t = V (t_o, i_o, j_o, p (t_o - \Delta t)\ \sin$$

$$(p (t_o - \Delta t))\ \Delta t.$$

The derivatives are then approximated at the grid points assuming that the grid distance is unity hence

$$\Delta t \frac{dV_k}{dx_i} (i_o, j_o) \simeq (V_k (i_o + 1, j_o)\ \Delta t - V_k (i_o - 1, j_o)\Delta t)/2$$

and

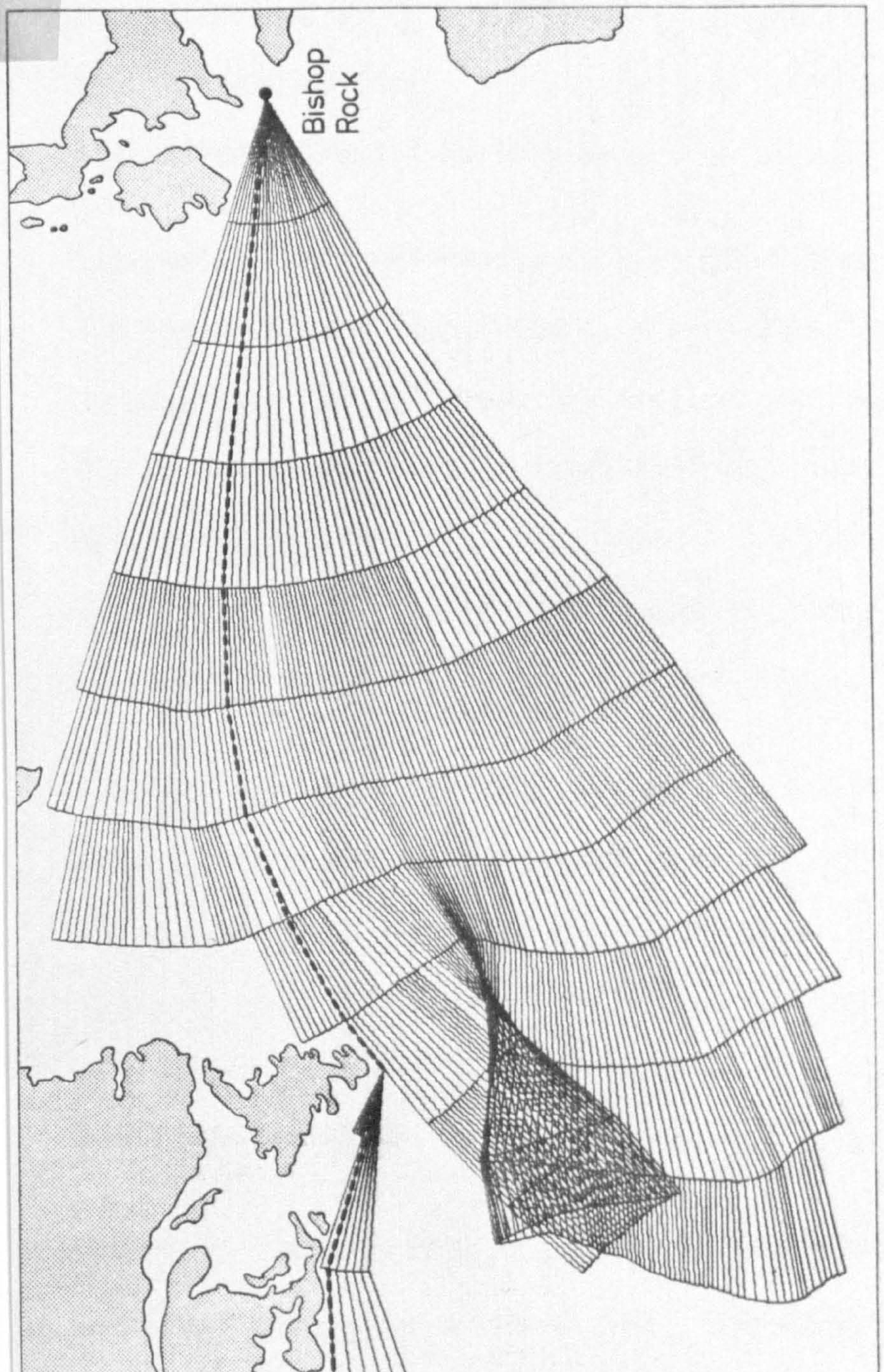
$$\Delta t \frac{dV_k}{dx_2} (i_o, j_o) \simeq (V_k (i_o, j_o + 1)\ \Delta t - V_k (i_o, j_o - 1)\Delta t/2 (k=1,2)$$

The derivatives at points between grid points are calculated by linear interpolation. Thus once $\lambda_1 (t_o)$ and $\lambda_2 (t_o)$ are calculated an optimal course angle $p(t_o)$ is determined using the velocity diagram at the point $(x_1(t_o), x_2(t_o))$, where the wave information of both height and direction is also calculated by linear interpolation. It follows that once the course angle $p(t_o)$ is established a new point is reached after a time step Δt.

The procedure is repeated calculating multipliers $\lambda_1 (t_o + \Delta t)$ and $\lambda_2(t_o + \Delta t)$. For successive time fronts the multipliers are calculated for components of the vector V which is perpendicular to the time front S at the point of intersection at the front.

The angle $\alpha(t_o) = \arctan (\lambda_1(t_o)/\lambda_2(t_o))$ is the angle between the normal on a time front S and x_1 axis of the grid. Here the time front S is defined as the locus of points which can ultimately

Fig 6.3



Computer produced by means of an incremental plotter using wave information over the period 17 January-23 January 1970, fictitious ship's data and a 12-hour time step. The least-time track is indicated by the dashed line.

Reproduced by permission of de Bilt Meteorological Bureau be reached from the origin after n time steps Δt_n.

It is assumed that the λ values are continuous across S and may be defined at $t_o - \Delta t$ for the λ_1, λ_2 preceding extremal and thence used for $t_o + \Delta t$. They are then redefined for successive extremals by this updating process.

Extremes of adverse weather such as heavy beam seas, fog or ice limits may be identified by their respective grid co-ordinates to establish "no-go" areas for a particular vessel. Radials may be truncated to avoid subjecting the vessel to these extremes, by careful programming. The figure 6.3 shows a computer produced least time track from the Bishop Rock to Nantucket Shoal as produced at the de Bilt Meteorological Bureau in Holland.

6.2.3 Shore based routeing methods

The example given in the previous section for computation of the least time route is one of several methods in use. In this author's view, it represents the clearest and most effective method of several methods studied; of course all methods relate to the basic control theory equations discussed (6(xi) - 6(xv)).

The first computer models used in shore based routeing employed the classic theories of JAMES (*52*), see de WIT (*27*), in what may be termed mathematical heuristics. This class of algorithm applies traditional manual routeing procedures into a formal mathematical model, whereby an ultimate time front will reach the destination and the minimum time track is thereby retraceable to the origin. Computer application of this clear and basic method is cumbersome as random errors arise when computing a normal direction, although application with a video display allowing manual over-ride and assistance in sorting out confusions which may arise in the vicinity of a depression, may alleviate this to some extent.

More sophisticated models developed throughout the sixties involve the use of iterative methods. One type involves the use of first derivatives, such as steepest descent/ascent or method of gradients, R.A. GREGOR (*42*), BRYSON and DENHAM (*12*). This approach has inherent difficulties of course convergence which makes the application to a true least time track difficult. A more efficient approach uses second order derivatives of the speed function and also includes variational relations between initial and end values, W. MARKS (*66*), F.D. FAULKNER (*33*), but the solution depends largely on the choice of initial course.

The model developed through the seventies at the Massachusetts Institute of Technology by E. FRANKEL and H. CHEN (*36*), goes a long way to removing these weaknesses, by using a "Forth and Back" iteration procedure in a new dynamic programming strategy. In its concept the new algorithm is similar to those discussed above, however, controls are set for each state based on minimum time and/or minimum cost criteria. The repetitive forth and back procedure smooths the operation and allows for improved convergence to an optimum route.

All of these methods use wave data for the first 72 hours by theoretical generation from forecasted wind fields, as discussed in Chapter 2. The American models thereafter base decision making on an analogue wave data store, A.J. KLAPP (*56*).

From day 3 to day 10, radials and time fronts are generated by interrogation of an historical wave height forecast for a particular sea area based on a "best-weather" pattern for a twenty-eight year period. After day 10, monthly wave climatology is used to route a vessel to its port of destination. It is also usual to adjust the vessel's speed by using monthly mean current along the entire route.

It is my view that the use of such historical wave data and wave climatology upon which to base decisions in order to "weather route" a ship in the middle latitudes of the baroclinic zone is a non-sequitur.

On occasions it may be dangerously misleading. It does, however, have valuable applications in the lower latitudes of the sub-tropics, in trade winds and monsoon areas.

6.3 Fuel consumption

6.3.1 Routeing for minimum fuel consumption

Fuel oil is now one of the major cost elements in the expenses of a voyage. Prices have increased by an order of magnitude in twenty years. Owners in certain instances may consider that the minimising of fuel costs for an ocean passage is the main routeing criterion.

The speed V is used as a new control variable and we assume that the rate of decrease of fuel may be defined as

$$\frac{dx_o}{dt} = f_o\,(t,\ x_1,\ x_2,\ V,\ p) \qquad \ldots\ 6(\text{xix})$$

where $\frac{dx_o}{dt}$ represents the change in use of fuel over the period of time t.

According to the optimal control principle previously discussed (Section 6.2.1) we now seek to find functions p(t) and V(t) to satisfy the equations formulated in Section 6.2.2. Thus

$$\frac{dx_1}{dt} = V \cos p + S_1 (t, x_1 \ x_2)$$

and

$$\frac{dx_2}{dt} = V \sin p + S_2 (t, x_1, x_2) \qquad \ldots 6(xx)$$

with

$$x_i(o) = x_{io}, x_i (t_1) = x_{i1} \ (i = 1,2)$$

hence for a minimum

$$\int_o^{t1} f_o (t, x_1, x_2, V, p) \, dt \qquad \ldots 6(xxi)$$

the speed V is restricted to a range of values given by

$$V \min (t, x_1 \ x_2 \ p) \leq V \leq V \max (t, x_1, x_2, p)$$

V max denotes the maximum service speed depending on wave height and direction as arrived at from ship performance data whilst V min denotes an acceptable minimum which may be established by reference to fuel consumption/speed data from previous voyages of particular vessels.

Assuming as stated above that V lies between the boundaries defined and letting:

$\lambda_o = -1$, and ignoring S, (the current), the control theory yields:-

$$- f_{ov} + \lambda_1 \cos p + \lambda_2 \sin p = 0 \qquad \ldots\ 6(xxii)$$

and

$$- f_{op} - \lambda_1 V \sin p + \lambda_2 V \cos p = 0$$

where

$$\frac{d\lambda_1}{dt} = f_{ox_1}$$

$$\frac{d\lambda_2}{dt} = f_{ox_2} \qquad \ldots\ 6(xxiii)$$

From this theory S.J. BIJLSMA (*9*), has shown that the speed V along an extremal must be so chosen that it maximises the quotient.

$$\frac{V}{f_o(t,\ x_1,\ x_2,\ V,\ p)} \qquad \ldots\ 6(xxiv)$$

Thus at every co-ordinate point in the (x_1, x_2) plane, an optimal speed V (t, x_1, x_2, p) satisfying the above equation may be calculated in conjunction with the exercise previously explained for a least-time route.

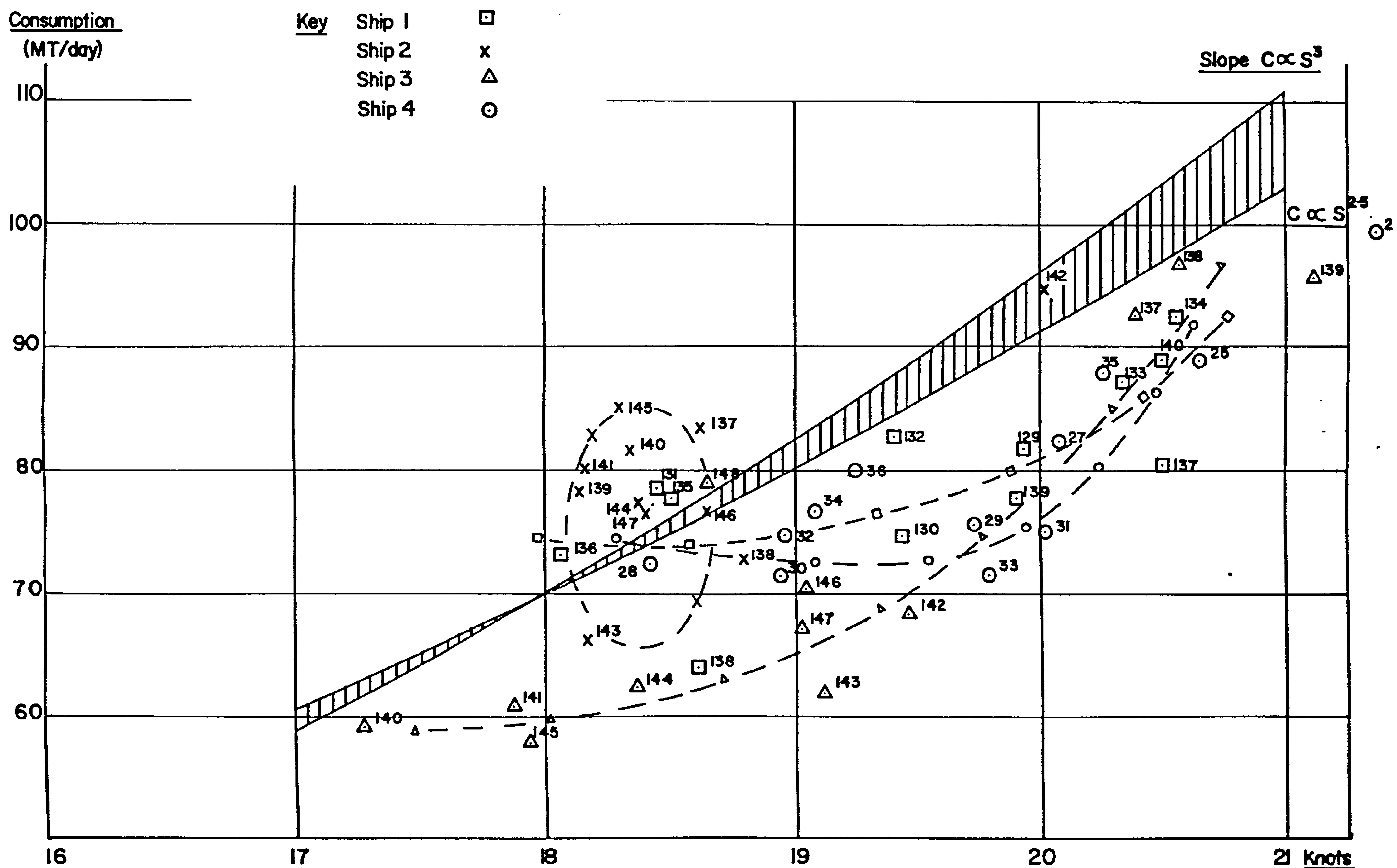
6.3.2 Fuel consumption (case study)

Data collected from four container ships operating on the North Atlantic trade were analysed. The data ensued from analysis of voyage abstracts and general voyage reports. It is raw data, that is to say, uncorrected for slip, stoppages, charterers instructions or any other factor.

Three of the vessels are sister ships and the fourth of a very similar size and type. Each North Atlantic round voyage

FIG 6.4 (a)

VESSELS - HFO CONSUMPTION V AVERAGE SPEED (EASTBOUND CROSSINGS) 1980



for these vessels is of approximately one month duration and the data represents some forty seven voyages and ninety four crossings of that ocean.

Fuel consumption "C" in metric tonnes per day was regressed against average voyage speed "S" for both east-bound and west-bound passages (see Figures 6.4(a) and (b) respectively) to yield the Speed/Consumption curves indicated.

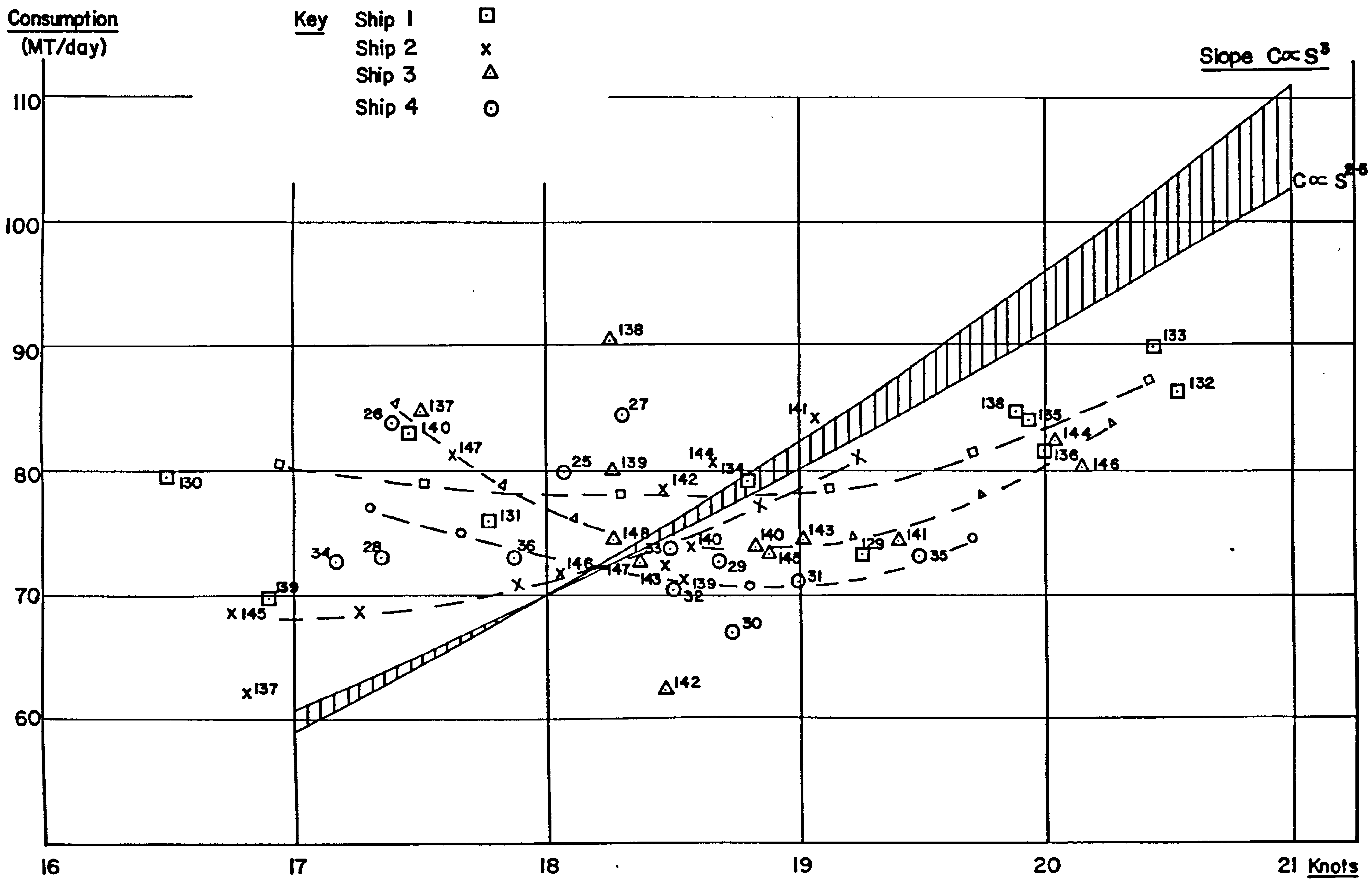
Theoretical curves of consumption C against speed S are plotted through an arbitrarily chosen datum point of 70 metric tonnes per day and 18 knots speed to obtain the theoretical trends of $C \alpha S^{2.5}$ and $C \alpha S^{3.0}$ as a comparison with actual vessel performance.

Reference to Figures 6.4(a) and (b) shows little relationship to these theoretical trends. In fact in most cases an increase in fuel consumption is shown at speeds of one or two knots less than the general service speed. This was the case for both west and east-bound passages. The only exception to this general rule was Ship 2 (x) for which a regression line was considered to be unrealistic for the east-bound crossings due to the localised data. Discussion with the company management and analysis of voyage reports suggested that the performance and operation of this particular vessel was somewhat unreliable.

Obviously the four vessels referred to were not in the same sea areas at the same time when logging these data and therefore were subjected to varying degrees of weather and sea states. Thus although the vessels are of similar type it is not surprising that there exists a wide scatter of plotted co-ordinates with

FIG 6.4 (b)

VESSELS - HFO CONSUMPTION V AVERAGE SPEED (WESTBOUND CROSSINGS) 1980



little allegiance to the theoretical plotted gradients shown.

The most efficient passages are located in the bottom right quadrant of the diagram re: where the lowest fuel consumption coincides with fastest speeds and the least efficient voyages conversely are grouped in the upper left quadrant. Clearly, the more a ship master can trend his co-ordinate points to the "South and East" of the performance grid, the more commercially efficient will be his operation (purely from the fuel consumption point of view).

Closer analysis of individual voyage reports reveal the many influences which impinge both on the voyage speed and overall fuel consumption. As the data used is subject to anonymity I will give a general list of these influences without specifying particular voyages. Thus:

Ship influences:

Autopilot defective, vessel proceeding on hand steering.

Engine breakdown. Changing defective valves.

Unexplainable shortfall in engine performance.

Too deeply ballasted.

Environmental influences:

Several reports of gale force winds (six separate voyage reports).

Weather poor, high swell.

Heavy weather a major problem.

Delayed 24 hours by bad weather.

Hove to for six hours in heavy seas.

High slip due to bad weather and severe swell.

Severe storm.

At least three separate gales (hove to in one).

Course and speed adjusted to minimise pounding.

High winds and confused swells for three days.

Severe weather and high slip (15.6%).

Southerly course taken to avoid Hurricane Earl.

Of the reported environmental influences affecting the vessels' performance only one of the seventeen reports which specifically cited extremes of weather as a cause was for an east-bound passage.

Referring to the performance curves for a similar vessel, the DART ATLANTIC, Fig. 3.4, a 3% loss of performance is indicated for following seas, whilst a loss of almost 20% is recorded for head seas for Beaufort force 8 gale conditions. The same absolute conditions apply but the relative effect on vessel behaviour is completely different.

Consequently a watchkeeping officer may view a gale from ahead very differently from an astern aspect when allocating a Beaufort number to the existing sea conditions.

No coherent or comprehensive programme of weather routeing was conducted by this company or the vessels mentioned above during the 1980 season under scrutiny, although individual masters may have taken independent action in the light of weather forecasts received on board.

Table 6.1

Atlantic Crossings with extremes of average speed

Table 6.1	Voy.numbers	Ship 1	$\boxdot$	Ship 2	×	Ship 3	Δ	Ship 4	θ
West Bound Crossings	below 18 knots average speed	130 131 139 140	Jan Feb Oct/Nov Nov/Dec	137 145 147	Jan Sept Nov	137	Jan	26 28 34 36	Jan March Sept Nov
	above 20 knots average speed	132 133 136	April May Jul/Aug			144 146	Jul/Aug		
East Bound Crossings	above 20 knots average speed	133 134 137 140	May June Aug/Sep Dec	142	June	137 138 139	Jan Feb March	25 26 27 31 35	Dec Jan Feb June Oct

6.4 Ship Based Weather Routeing Model

6.4.1 General Philosophy for a Ship-Based Model

During the decade directly preceding the writing of this thesis the author served as master or chief officer on five vessels all equipped with facsimile receivers. All of these vessels traded in the North Atlantic Ocean for either part or the whole of the voyages mentioned. The vessels referred to are contained in the Table 6.2 below:

Table 6.2

Vessel types experienced

Vessel	Type	Voyage
S.T. Gondwana	V.L.C.C.	Arabian Gulf to Marseilles
S.S. Omoa	Reefer	Abidjan/Le Havre/ Southampton
S.S. Scythia	Reefer	Dover to Turbo (Colombia) Turbo to London
M.V. Dart Atlantic	Container ship	Southampton to E. Coast U.S.A., U.S.A. to Southampton
M.V. Queensgarth	Ore-Carrier	Birkenhead to Port Cartier, Port Cartier to Liverpool

Whilst serving on these ships the author was in a position to develop the basic ideas mentioned in a previous publication MOTTE (77). With further practical experience at sea a working model was formulated which was refined in the light of experience gained.

Further work has ensued as a consultant and adviser on sea going operations to DART CONTAINERS LTD. and B.P. SHIPPING LTD. (21).

This recent work and my previous regular seafaring as a deck officer and ship master from 1953 to 1964 lead me, (together with the aforegoing theoretical appraisal) to certain conclusions in formulating a procedure for weather routeing to be conducted from on board ship.

These views are directed at a model for the North Atlantic Ocean, for ocean crossings in middle latitudes or, in meteorological parlance, the baroclinic zone. They are also applicable to ocean passages in middle latitudes in all other oceans. As has been previously stated (Chapter 5), depression frequency is of the order of one depression per week in the North Atlantic and the life cycle of a depression is also of this order. Coincidentally a modern vessel capable of some twenty knots is on a North Atlantic passage for one week. Thus on average the operators of the vessel will need to consider the position of the vessel relative to one and possibly two depressions per ocean transit.

On east bound passages, as a vessel will be travelling with the general movement of the depressions, the relative rate of approach of vessel to potential storm is decreased. Conversely, on a west bound passage the velocity of the wave is added to the wind velocity and the velocity of the vessel, to give a high rate of approach and of course a greater likelihood of adverse seas affecting vessel performance. Indeed claims of shore routeing agencies in saving time on recommended routes for east-bound passages are usually of the order of one hour only for the total passage, whilst ten hours is the order of time saving claimed for west-bound passages after several crossings have been averaged, D. HEIJBOER (*44*). In Section 6.3, Table 6.1, it is observed that the vast majority of sub-eighteen knot passages are experienced on west-bound passages whilst rapid passages conversely apply when east-bound. This places the demand for routeing heavily onto the west-bound leg of the transatlantic voyage. My seafaring experience, referred to on the Atlantic trade, reinforces the above findings.

Computer models discussed in Section 6.2 are used to generate a variety of routes. A least time route may then be identified subject to the limitations of the optimal control theory and the mechanics of the operation. The set of equations used are constrained so that the least summation of the differentiable multiplier λ_i, is sought and differential changes in the co-ordinates of the end point of radials are connected by equation 6(xv).

Thus the computer is programmed to calculate one theoretical least time track. Any other strategic route which may be followed by a vessel necessarily requires a subjective choice by the operator. The least time track as calculated depends on the accuracy of the chosen differentiable multiplier, obtained from reference to the forecasted or analogued sea state as applied to the response characteristics for a particular vessel. The wave height if obtained from a standard wave forecast chart is derived from a surface prognosis evaluated wind speed as explained in Section 2.3.2. (If obtained from historical wave data it may bear no resemblance whatever to the actual prevailing conditions).

Integration errors will inevitably have occurred in the production of the surface prognosis and these errors together with transferred errors of the wave equations used will have an accumulative effect. (For example, an assumed swell factor in the Scott formula as used at Bracknell, equation 2(xxiii) may not be applicable). The author is well aware that such assumptions have to be made when calculating a least time track. Much time, expense and scientific reasoning has been expended to this end. I believe that because of the attendant errors which are inherent in such calculations that the practical application of a least time route to vessels at sea has distinct limitations. The modern back and forth iterative method of route determination is dependent on analogue wave data for a complete picture and therefore must be suspect for mid-latitudes, where a transient weather mode is the norm.

Further, a route purely advised on criterion of time may have little regard to the safety of the vessel or the possibility of sustaining heavy weather damage. Although of course programmed sub-routines can modify for this more strategic approach, 6.2.2.

Necessarily, a subjective element must arise in an onboard model for several reasons. Although time on passage is fundamental to most ship masters' thinking, especially on the highly competitive container trades, in all cases this will be of secondary importance when considered relative to possible storm damage or the placing of the vessel in hazard in any way. A least time track alone does not take full regard of this premier requirement.

(The continued ship losses suffered by foundering (Section 3.2.3) show room for improvement in the general philosophy of voyage planning)

It is also not usual to have either computer facilities on board ship or for the deck officers to be trained in their use. This is no longer an unsuperable problem as the small desk computers with visual display units of 32K store and more are available at modest prices. These machines are ineffective for the models discussed in section 6.2.2 but are easily programmable to obtain a set of radials from a sea state chart to assist in the general navigation calculations of a ship based model.

A computer is only vital to the weather/routeing exercise when several ships are to be routed simultaneously and least time tracks are to be generated.

Rather then, routeing should be conducted with the fundamental philosophy of storm or gale avoidance. A rigorous analysis of an individual vessel's behavioural characteristics and therefore performance related to relative wind force and direction should be undertaken to learn and catalogue the limitations of environmental conditions to which that vessel should be exposed.

It then follows that a good estimate must be made of:

(i) the short term prevailing conditions that the vessel may immediately experience on departure;

(ii) the medium term or mid-ocean development of depressions;

(iii) the long term or far ocean features likely to occur before the vessel completes her passage.

The sole source for such a detailed analysis is provided by the facsimile transmissions discussed in 4.2 and 4.3 and received on board via a marine facsimile receiver.

Following the theory discussed in 5.1 on the structure of the baroclinic storm and 5.2 on the steering indication obtaining from analysing 500mb flow patterns with reference to trough line cant, the aforegoing philosophy may be fulfilled.

6.4.2 Facsimile information for use in a ship-based model

Storms have three spatial dimensions and as they move and change their form, the fourth dimension of time is evident. Thus a four dimensional consideration of the atmosphere is necessary in planning to avoid the worst effects of these middle latitude phenomena.

The time element is incorporated by reviewing successive data chronologically, and the three spatial dimensions by observing developments at various levels in the atmosphere but with particular reference to the 500mb steering level when considering storms of tropospheric extent. It is of only limited value to attempt to route vessels on the evidence of surface information alone. It is always necessary to have an indication of storm movement and future development particularly for the second half of the passage in question. Such indication is only attainable with the assistance of upper air information to evaluate growth and steering likelihood of depressions as indicated in 5.1 and 5.2.

Table 6.3

Facsimile data reception for ship-based routeing

Chart \ Time		FORECASTS 24 hour	48 hour	72 hour & 96 hour	TOTAL CHARTS REC'D
Surface North Atlantic	*1,2,*3, *4,5,6	1,2,3, 4,5	1,2,3, 4		15
Surface Circum-polar	1,2,3, 4,5				5
Wave	*1,*2,*3, *4,5,6	1,2,3, 4,5	1,2,3, 4		15
500mb	*1,*2,*3, 4,5,6	1,2,3, 4,5	1,2,3, 4	1,2,3	18
Ice	2				1
Nephanalysis or Satellite Picture	*1,2				2
				TOTAL	56 charts

Number indicates DAY of routeing

*Charts shown in Appendix VI

The Table 6.3 lists the charts necessary for the completion of a comprehensive routeing exercise. They are all available from each of several transmitting stations as explained in 4.2.

6.4.3 A ship-based model

Bearing in mind the philosophy expounded in 6.4.1 the decision making processes for storm avoidance may be categorised as

1. Short term: (covering the first three days of passage)

   The surface analysis and 24-hour, 48-hour surface prognosis charts together with related sea state information enables the operator to prepare the initial part of his voyage.

   The wave aspect is noted and with reference to the performance data (Section 3.3.3) a family of radials may be drawn at twelve or twenty-four intervals giving time fronts of progression, by the joining of the extremities of the radials.

   As explained in 6.1.3 a value for prevailing current 'S' may be added to the radial lengths.

   This initial exercise has been explained together with examples by JAMES (51), MOTTE (77). However, decisions taken at the outset solely on this surface information may be completely misleading, a more comprehensive picture is provided by reference to 500mb flow, thus:

2. Medium term: (covering day two to day four of passage)

   Depressions are identified in the short term analysis and reference to the 500mb level will reveal the degree of cant of the trough line of each storm. As was explained in Section 5.1.3 this will indicate the state of development of the depression and give some measure of whether it is likely to increase or decrease in strength in the outlook period and therefore enable the operator to decide on the amount of course alteration necessary to bypass the worst effects of the storm.

Further it will assist the operator to evaluate the efficiency of the steering principle obtaining from an overall analysis of 500mb flow for a long term view. (see steering case study section 5.2.2).

3. Long term: (covering day two to day six of passage) The 500mb flow enables the operator to apply a comprehensive pattern to his decision making. However, this will differ on west and east bound ocean passages. In Section 5.2.2 a case study of the degree to which North Atlantic depressions were steered by the 500mb flow indicated a strong relationship between depression tracks and 500mb streamlines on the western side of the ocean.

Thus assuming that the depression troughs are seen to be canted appreciably (by more than 400km displacement between surface and 500mb level) the 500mb flow will indicate the future tracks of depressions showing a "swept area" of ocean to be avoided.

This long term strategy will of course impinge on any short or medium feed-back system between all three levels of decision making. On occasions these term indications may be in phase and bias a planned course in one direction, say north of the great circle track, for example, on other occasions they may give conflicting evidence such that a short term measure will suggest an initial track north of the great circle with a final track to the south suggesting a strategic sinusoidal configuration about the great circle track.

It is usual for the baroclinic wave to be growing when situated on the west side of the ocean as it is in a balanced thermodynamic condition with a trough line necessarily canted well to the west with height (Section 5.1.3). It follows that it is usual for the steering principle to apply here. Thus the long term strategy outlined on a west-bound passage is viable.

However, there will be instances, conceivably, when the analysis may indicate a quasi-vertical trough when application of the steering principle will be suspect.

For east-bound passages a comprehensive view of weather conditions will be more difficult to ascertain as depressions mature on transit to theeastern side of oceans and less reliability may be placed on the steering principle. As has been explained in 6.4.1 and demonstrated in 6.3.2, the routeing requirement for vessels on east bound passages is less marked because of the relative directional flow of storm and ship. Air flow relative to the depression rather than relative to fixed axès on earth was considered in Chapter 5. Hence ship movement relative to the depression rather than the usual navigational grid of the earth will demonstrate the difference in effect of the storm on east and west-bound passages. Indeed, should a vessel leave her departure port, say on the eastern seaboard of the States, for the U.K., between the passages of two depressions she will be in company with a transient ridge giving her the likelihood of a trouble free passage. This is of course making the assumption that the depressions and the vessel travel at similar speeds. This may well be the case with fast container vessels, thus it can be observed that the TIME of departure can be critical especially for fast vessels on these eastbound passages. Nevertheless, the strategy of short, medium and long term integrated decision making will apply for both west and east-bound passages.

FIG 6·5 overlay 1

TEXT BOUND INTO

THE SPINE


Longitude. 80 70 60 50 40 30 20 10 0 10
60 Volume 22 No 040
DE BILT METEOROLOGISCH INSTITUUT
1200GMT FEB 9th – 13th inc
CHART of COMPOSITE SEA STATE
wave height in metres } Sea
wave height in metres } Swell
pack ice limit
DAY 1 MON 9th
DAY 2 TUES 10
DAY 3 WED 11
DAY 4 THUR 12
DAY 5 FRI 13
H
L
FIG 6.5

FIG 6·5 overlay 2

ROUTEING STUDY

The figures 6.5 show an actual study of two vessels, sister ships, denoted Ship A and Ship B. Ship A was not routed and Ship B followed the ship-based routeing procedure outlined. The relevant surface, 500mb and sea state charts are included in the Appendix VI.

Refer Figure 6.5 and Table 6.4 Ship Routeing Exercise

SHIP A: Voyage planning was decided on the evidence of surface analysis and surface prognosis information alone. No attention was focused on upper air information. No analysis of growth potential of depression L_L or depression L_s was made. A near great circle track was followed up until February 10th at 0000 hrs when a more southerly course was set some 10^o from the great circle route. On February 11th the vessel was hove to experiencing eight and nine metre wave heights from ahead. 15.2 knots was averaged for the day.

Two containers were badly damaged by breaking seas and the vessel suffered some slight structural damage. The course was adjusted to a more southerly aspect as shown in Figure 6.5 to allow the vessel to meet the seas more comfortably and to skirt the storm.

On February 12th a course was set for Halifax. The vessel arrived at 0100 (Z) on 14th February averaging 18.78 knots for the voyage.

SHIP B: A comprehensive routeing procedure was followed according to the ship-based model previously discussed.

1. Short term analysis

   The surface analysis, prognoses and related sea state charts were studied. Radials were constructed and loci drawn.

2. Medium term analysis

   500mb analysis and prognosis charts were analysed in conjunction with surface information to ascertain the structure, potential growth and steering influence on depression L_L and L_S. Figure 6.5 overlay 2 reveals the results of this analysis. It is evident that both L_L and L_S have canted trough lines with 550km and 1100km values respectively, for the first day of routeing. The likelihood is that both of these depressions will grow (L_S very rapidly) and both will be steered.

   500mb prognosis charts and surface prognosis indicate a general south-easterly movement of low L_L. With these points in mind a course is set some 5^o north of the great circle in the short term, although the long term analysis indicated a strategic route well to the southward.

3. Long term analysis

   The extended 500mb prognosis indicates a well formed flow which will take depression L_S to the north towards Iceland. However, the extreme trough line cant and the cold polar incursion of air behind the cold front indicates a thermodynamically balanced system which is likely to develop L_s to storm force. Upon skirting L_L a more southerly course is set on the 10th February, some 40^o south of the great circle. Ship B then proceeds to a strategic position of 46^oN latitude in 30^oW longitude ahead of the storm L_s, but able effectively to pass to the southward of its most extreme effects. A $15ms^{-1}$ mean velocity component was allowed from the total velocities afforded from 500 mb streamline indication. Vectors were thus plotted, Figure 6.5 overlay 2, to indicate future storm positions.

The vessel made up for Halifax on 0000 hrs on 12th February and recorded an average speed of 19.95 knots, more than one knot faster than Ship A, arriving in Halifax at 1700 (Z) hours on 13th February some eight hours ahead of her sister ship. More importantly without having suffered any heavy weather damage either to cargo or hull. It is the comprehensive view that a structural analysis of the storm affords which allows early action to be taken as illustrated. A surface view alone, as for Ship A, is insufficient to base a comprehensive and effective routeing plan. Inevitably any action is taken too late and although some of the worst effects may be avoided as in this case, some heavy weather damage has ensued to this vessel.

The Table 6.4 shows that the routed vessel steamed a distance of 2,494 nautical miles some 52 miles further than Ship A and 154 miles over the great circle distance.

It is estimated that a similar type of vessel proceeding on the great circle course shown as a comparison would have arrived some twelve hours later than Ship B and 4 hours behind Ship A. The great circle distance is 2,340 miles from the Bishop Rock to Halifax. It should also be noted that adherence to the great circle route over this period of time would have placed a vessel in a position where she would have experienced a significant wave height of the order of ten metres and would thereby be needlessly placing her cargo and hull to potential sea damage.

One week later (departing Le Havre on February 17th) a similar vessel to A and B was given routeing information by this author to follow the great circle route to Halifax. Daily messages confirmed this route as the best throughout the passage. This emphasises the need to plan voyages on immediate rather than historic, climatological data.

Note: *The performance curves Figure 3.4 relate to the live example Figure 6.5.*

Table 6.4

A Ship-based Model (Results)

Table 6.4 — Feb.'81 Date & Time	BISHOP ROCK TO HALIFAX (N.S.)					
	SHIP A			SHIP B		
	Sea State m.	Speed kts.	Day's run nm.	Sea State m.	Speed kts.	Day's run nm.
Off Bishop 1200 8th to 0000 9th February	2A	19.9	239	2A	20.0	240
0000 10th February	4A	19.3	463	3A	19.7	475
0000 11th February	6A	18.0	432	2A	20.2	485
0000 12th February	8/9A	15.2 hove to	365	6/5A	18.8	451
0000 13th February	7/6B	18.5	444	3B	20.4	490
to arrive Halifax	2B	20.0	499	2B	20.2	353
Time of Arrival	0100 on Feb.14	18.78 av.sp.	2442	1700 Feb.13	19.95 av.sp.	2494

A Ahead seas

B Beam seas

7. CONCLUSIONS AND RECOMMENDATIONS

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Constraints

7.1.1 Ship based or shore based

There are many voices continually heard justifying the shore based weather routeing service. My day-to-day contact with serving ship masters simply does not reinforce the degree of success claimed by some routeing agencies. It is understandable when a commercial service is offered and considerable outlay has been invested in expensive computers with attendant hard and software that some justification is demanded.

The author believes that weather routeing is of great benefit when traversing an ocean in middle latitudes. On occasions it will be vital, usually on west-bound passages in winter time, regardless of whether the exercise is conducted from on-shore or on-board. An effective ship based model has been evolved based on both theoretical and practical knowledge of meteorology and navigation. I do not make any claims that the ship based routeing model I have outlined in this work is more effective than the service afforded by shore agencies. But it may suit some ship masters, for example, on regular North Atlantic trades to be in a position to plan their own routes. "The master of a ship is ideally the best person to choose the route that his ship will follow". G.V. MACKIE (*65*), with the proviso that a shore agency is in more immediate possession of more weather data and because of the sheer number of crossings analysed and advised, each operator has a wealth of experience of routeing mechanics unmatched by the most experienced of ship masters.

On the other hand a ship master knows his ship and its behavioural responses over a variety of conditions of trim and loading, and is also on the spot to make allowances for local weather conditions and variations from the forecasted weather pattern which may occur. Several masters have made the comment that shore routeing tends to remove the initiative from them as commanders of their vessels. If this is the case the alternative is to adopt an onboard routeing procedure such as I have outlined with all the attendant work and responsibilities that this involves. Necessarily the operator will have to come to terms with the complexities of the baroclinic wave. In effect he has to understand the workings of the enemy as outlined in Chapter 5. He has to extend his knowledge of the atmosphere beyond the minimum requirements specified for the Master Mariner Certificate of Competency that he may currently hold. He will need to avidly study all information available from the facsimile networks as catalogued in Chapter 4. Above all he must continually practice the outlined methods of routeing, thus gaining experience. The final rewards will justify this energy input; after all, this is seamanship using modern equipment for the best safety of the vessel.

I have already mentioned what I believe to be the red herring of the least time route. When ship routeing services commenced, the main objective was to reduce passage time regardless of other considerations. This has led to the reliance on computers for application of optimal control theory. When many ships are to be routed simultaneously, of course a computer will be a necessary tool. For the storm avoidance, least damage to hull and cargo, single ship operation described in Chapter 6, a computer is not necessary, although it may on occasions be most useful.

7.1.2 Limitations of the model

The decision assisting model outlined, relies on an understanding of the structure and behaviour of a growing baroclinic wave. Thus the application of the model is confined to middle latitudes for trans-ocean passages. The areal expanse of a depression may necessitate large deviations from traditional routes, so the theory is applicable to generally unrestricted navigable waters. Because of the general pattern of steering the model is more useful on west-bound passages. It has been demonstrated that this coincides with the greatest potential savings.

The emphasis is on a technique of storm avoidance, thus minimising heavy weather damage. The concept of a minimum time route may, on occasions, be misleading. The procedure outlined facilitates the computation of a "strategic" route. The use of 500 mb charts as a steering indicator must always be constrained by an estimate of trough displacement or cant (Steering case study). This assumes a storm to be of tropospheric extent. Smaller disturbances, such as polar lows will have a lower steering level.

Construction of least time fronts from ship performance data related to sea state information, will incorporate almost every error of data analysis usually encountered in physical science: instrumental errors, observational errors, errors in application of standard formulae, integration errors derived from summation of differential equations and incompleteness of data. Hence the non-reliance of the least time route as a sole arbiter for decisions. It is the long term and medium decisions derived from extended 500mb forecasts which allow a broader view to be developed. Of course, errors will be evident here but outside the atmospheric boundary layer a greater reliance may be placed on the momentum and continuity equations, and the extended forecasts so derived. Reliability of forecasts in the prognosis charts used in any routeing exercise is always a natural limitation on the end product.

Optimistically, this accuracy has been and is being improved by modern technology. Mariners must be in a position to take advantage of these developments.

As the 500mb flow is dominant in the decision making process, it is evident that the most effective routeing results will obtain when the 500mb flow pattern is persistent. When complex transitional changes occur in the streamline pattern, the application of the model is less effective and shorter term decisions may prevail.

As the vessel nears the port of destination, there is less opportunity to deviate from the straight line route, hence transitional changes may occur with little remedy available to avoid extremes of bad weather. This is an unavoidable constraint of any routeing system.

7.2 Conclusions

7.2.1 Conclusions

The work presented here encompasses four main areas:

1. The application of optimal control theory to the navigation of ships in middle latitudes (Chapter 6).
2. An analysis of the growing baroclinic wave of middle latitudes, the mechanism of which has been explored to establish a steering correlation with 500mb flow related to trough line displacement (Chapter 5).
3. The wind-wave relationship is studied and various known formulae examined for application to routeing models (Chapter 2).
4. The behaviour of a ship in a seaway is examined with a view to the collection and presentation of effective ship performance data, suitable for use in a ship based routeing model (Chapter 3).

All of the factors discussed relate to the general philosophy of storm avoidance. Thus the discussion on the wind wave relationship and the vessel behaviour are constrained to this end. It is important to realise that it is the relative responses of wind to sea and the relative responses of vessel to varied sea states that is required rather than any accurate absolute assessment. A least time front is constructed which forecasts relative performance of the vessel on varied courses enabling a subjective choice to be made by the operator. As long as the general form and shape of this curve is accurate, it matters little should it be advanced or retarded in its absolute positioning. A subsequent update will adjust for any such inaccuracies.

The middle-latitude depression is associated with the gale and storm force winds which generate the heavy seas which in turn place the vessel in hazard. I have tried to direct my attention to this prime phenomenon rather than the secondary factor of the sea. The logic is to learn about the storm's structure, mechanism and behaviour with a view to avoiding it. Effective avoidance must lead to safer and smoother voyages and on occasions, as a bonus, the minimising of passage time. Better predictability of arrival time for vessels with massive unit loads, amplifies a further requirement. The general practice in the eighties is for short holding time in port with more specialist carrier units. Expensive terminal facilities are provided with a timetabled usage by a consortium. The programming of such an operation has to be done with a minimum tolerance of voyage time fluctuation, thus each vessel's schedule is important to the whole scheme. There is little requirement to reduce passage time, rather the demand is not to increase time on passage by perhaps heaving to in a storm for a day. This modern trend to specialisation and through transport systems tends to a demand for strategic routeing. The long term savings accruing by reducing heavy weather damage both to ship and cargo on strategic routes is the main reason, however, for adopting the procedures outlined. The penalties of "off-hire" clauses relating to overdue vessels on Time Charters, the carriage of sensitive cargoes and the susceptibility of damage to vessels in ballast, are more extreme specific cases for a storm avoidance approach.

Any ship master proceeding on winter middle latitude crossings of oceans without judicious regard to meteorological data or application of weather routeing procedures will, on occasions, be holding his ship at risk unnecessarily.

7.2.2 Recommendations for future work

This work has shown that a ship's route can be planned by having due regard to the structure and behaviour of middle-latitude depressions. Recommendations for future work must necessarily be directed towards an improvement in the physical understanding of these complex phenomena. Work is proceeding, notably by the Atmospheric Physics Group at Imperial College. It is important that this is not conducted with a closed ivory tower attitude. Information on developments should be disseminated to mariners, for example, where application of these theories may have tangible results, not the least of which may be to reduce the appalling losses of ships and life due to press of weather.

The European Medium Range Weather Forecasting Centre (E.M.R.W.F.C.) was established at Shinfield, England in 1979. This centre provides a service to the seventeen member nations only and not to individual requests or the general public directly. Basically the endeavour is attempting to extend the forecast by conventional deductive means, to a ten-day period*. Impressive computing facilities and peripherals with associated research continues to improve the accuracy of medium range prognoses. Eventually it may be possible to make the results regularly available via a separate facsimile channel to mariners regardless of nationality or vested interests.

**The information, at present, is contained in the form of daily 500mb and 1000 mb streamline charts which have obvious applications to the weather routeing principles discussed.*

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PLATES

Plate 1	M.V. DART ATLANTIC at sea.
Plate 2	Satellite photograph of Western Approaches to U.K. showing small depression, 10th February 1981, 0932 G.M.T. (Courtesy of Dundee University).
Plate 3	Facsimile receiver and display. (Muirhead U.K. Ltd.)

P L A T E S

(pages 148, 149, 150)

PLATE 1
M.V. DART ATLANTIC

PLATE 2

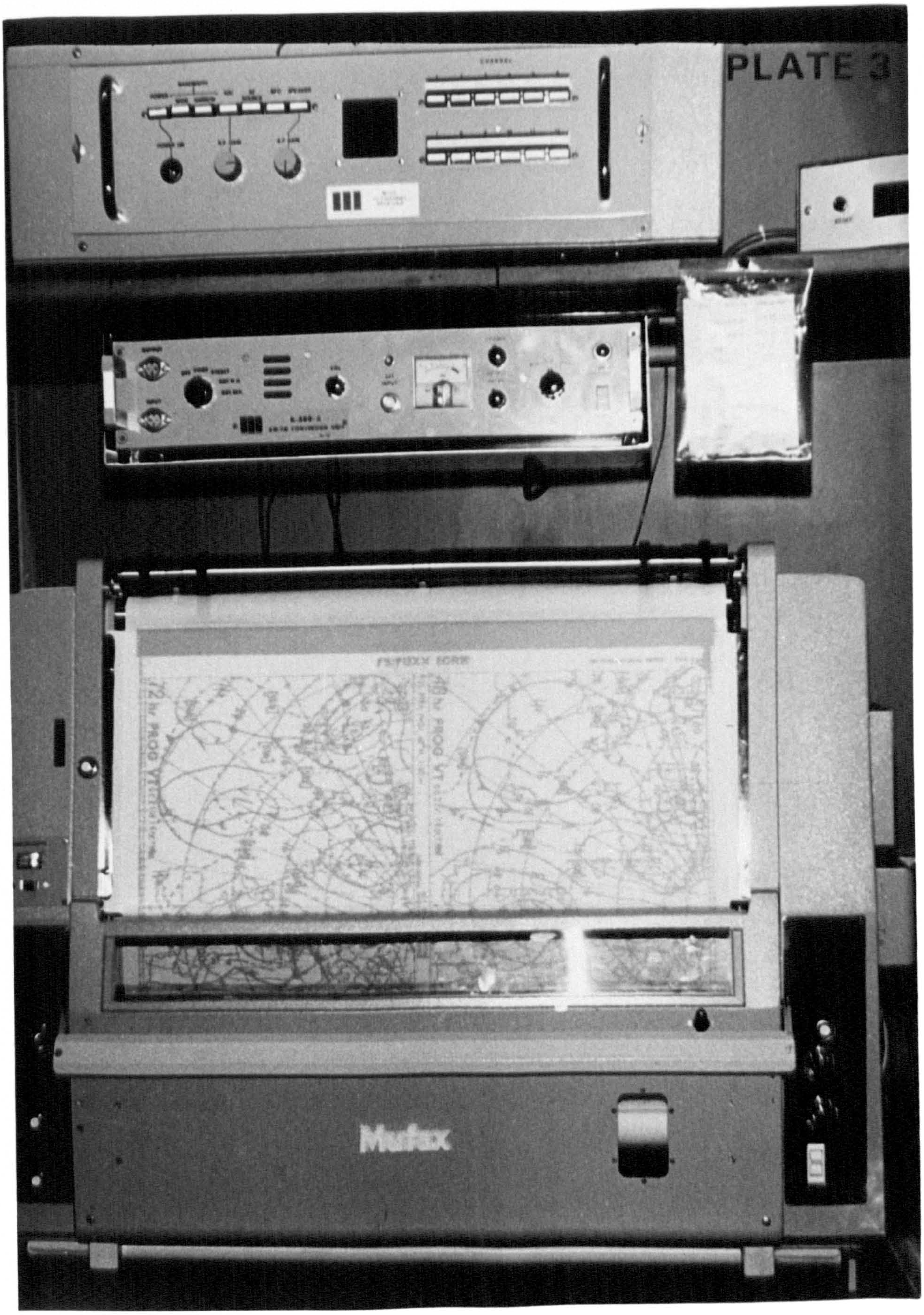


PLATE 3

APPENDICES

APPENDIX I The Multiple Regression Programme used in Chapter 3.

APPENDIX I

The Multiple Regression Programme

The many multiple regression calculations were executed on an IBM 1130 computer, using as a basis the following four IBM statistical subroutines:-

(i) Corre - to find means, standard deviations and the correlation matrix.

(ii) Order - to choose a dependent variable and a subset of independent variables from a larger set of variables.

(iii) Minv - to invert the correlation matrix of the subset selected by order.

(iv) Multr - to compute the regression coefficients, and various confidence measures.

Due to the complex nature of many of the independent variables, it is necessary that the computer should calculate them at the beginning of each program. This enables the raw data to be read in as a matrix, from which a second matrix containing all the independent variables is calculated. In order to change the independent variables, it is only necessary to change the variable-forming cards. Corre can then read in the second matrix, using a subroutine Data.

Several print-out options are available, depending on the choice of control cards. Firstly, the basic regression results can be printed out alone, as in the top half of Fig. 1. The two columns of figures at the top are the means and standard deviations of the twelve variables. Any selection of these twelve can be used in the main regressions; variables 5, 9, 10 and 11 being the wind, wave, sea temperature and displacement terms respectively. Variable

8 is the raw speed corrected for power and log error. The F-value indicates the overall significance of the regression.

Secondly, the residuals and corrected speeds can also be listed. In order to correct for all the independent variables used in a regression except one (e.g. power), the regression coefficients and intercept must be supplied as data with the control cards. The print-out from this is shown in Fig. 2, the values produced being those plotted for M.V. Dart Atlantic. In this case, the y-values are not power corrected. The figures above the heading in Fig. 2 represent the dependent variable, the number of independent variables used, and the independent variables.

.......DARTA

19.55308	1.16294
19.53171	1.19845
3.03627	0.17124
80.98236	502.16455
150.03781	540.19030
36.45102	35.09874
26.00483	31.57481
19.26842	0.68798
46.89720	39.55057
-2.31250	5.30417
0.34332	0.99509
19.52955	1.18710

VAR NO.	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF	COMPUTED T VALUE	INTERCEPT	STD. ERROR OF ESTIMATE	DEGREES OF FREEDOM	F VALUE
5	-0.00028	0.00009	-3.08455	19.92542	0.26378	43	69.10119
9	-0.01024	0.00107	-9.49241				
10	0.03954	0.00833	4.74405				
11	-0.12348	0.04586	-2.69248				

8 DEPENDENT

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL	CORRECTED SPEED
1	19.70029	19.67723	0.02305	19.94345
2	20.20932	19.77102	0.43830	20.36371
3	19.27023	18.94989	0.32034	20.24575
4	18.96969	18.81075	0.15893	20.08435
5	19.05624	19.24609	-0.18985	19.73555
6	18.45421	19.27150	-0.81728	19.10812
7	17.66468	18.38911	-0.72443	19.20097
8	18.09148	17.89303	0.19844	20.12385
9	18.41410	18.17566	0.23844	20.16385
10	19.47288	19.18191	0.29097	20.21638
11	19.64255	19.41497	0.22758	20.15299
12	18.86039	19.00102	-0.14062	19.78478
13	18.58017	18.62998	-0.04981	19.87559
14	18.66919	18.83139	-0.16219	19.76321
15	18.28003	18.73126	-0.45123	19.47417
16	18.58510	18.56141	0.02369	19.94910
17	18.54379	18.39407	0.14971	20.07512
18	18.06636	17.80294	0.26341	20.18881
19	17.85993	18.02870	-0.16876	19.75664
20	18.66027	18.44400	0.21627	20.14167
21	18.69714	18.74946	-0.05232	19.87308
22	18.68328	19.03574	-0.35245	19.57294
23	19.19430	18.93634	0.25795	20.18336
24	19.10611	19.06598	0.04012	19.96553
25	20.01109	20.13554	-0.12444	19.80096
26	20.19682	19.98073	0.21603	20.14149
27	19.93999	19.81412	0.12587	20.05128
28	20.11116	19.91739	0.19377	20.11917
29	20.00794	19.97349	0.03445	19.95985
30	19.93785	20.08309	-0.14524	19.78016
31	19.97839	20.03026	-0.05187	19.87353
32	19.26701	19.38424	-0.11723	19.80817
33	19.46677	19.48237	-0.01559	19.90980
34	19.63609	19.55648	0.07960	20.00501
35	19.81500	19.60049	0.21450	20.13991
36	19.60426	19.59709	0.00716	19.93257
37	19.47396	19.60262	-0.12866	19.79674
38	19.55584	19.62269	-0.06684	19.85856
39	19.49097	19.63124	-0.14026	19.78514
40	19.68077	19.80148	-0.12071	19.79759
41	19.60967	19.75246	-0.14279	19.78261
42	19.47032	19.55903	-0.08870	19.83670
43	19.55176	19.59291	-0.04114	19.88426
44	19.55101	19.44132	0.10969	20.03510
45	19.36988	19.39020	-0.02031	19.90509
46	19.55916	19.19332	0.46583	20.39124
47	20.56727	20.36695	0.20032	20.12572
49	20.20097	20.32345	-0.12248	19.80292

FIG. 1

12 4 5 9 10 11

CORRECTED SPEEDS USING INPUT REGRESSION COEFFICIENTS

CASE NO.	Y VALUE	CORRECTION	CORRECTED SPEED
1	16.99013	-0.24991	17.24003
2	21.09537	-0.15656	21.25193
3	20.24823	-0.97608	21.22431
4	19.92828	-1.11558	21.04386
5	19.96189	-0.68007	20.64197
6	19.41004	-0.65324	20.06328
7	18.66753	-1.53575	20.20328
8	18.89563	-2.03037	20.92601
9	19.36437	-1.74709	21.11147
10	20.48123	-0.74040	21.22163
11	20.62864	-0.50845	21.13709
12	17.39107	-0.92127	18.31234
13	17.10275	-1.29150	18.39425
14	19.62501	-1.09084	20.71586
15	19.28837	-1.19164	20.48001
16	19.45148	-1.36268	20.81416
17	19.33372	-1.52883	20.86255
18	18.76738	-2.12115	20.88853
19	18.82130	-1.89577	20.71707
20	19.44735	-1.47726	20.92461
21	19.44134	-1.17151	20.61285
22	19.64188	-0.88682	20.52870
23	20.08876	-0.98595	21.07472
24	20.00617	-0.85635	20.86252
25	20.92514	0.20849	20.71665
26	21.45362	0.05366	21.39995
27	18.44635	-0.11290	18.55925
28	21.03359	-0.00961	21.04320
29	20.86586	0.04643	20.81942
30	20.78731	0.15592	20.63138
31	20.86164	0.10338	20.75825
32	20.15867	-0.54250	20.70117
33	20.35563	-0.44442	20.80005
34	20.49401	-0.37045	20.86447
35	20.61915	-0.32711	20.94627
36	20.44808	-0.33042	20.77850
37	20.29231	-0.32449	20.61680
38	20.48942	-0.30432	20.79375
39	17.89088	-0.24560	18.13649
40	18.08067	-0.11835	18.19903
41	18.06711	-0.17365	18.24076
42	17.95634	-0.36597	18.32232
43	18.15883	-0.33078	18.48961
44	18.14609	-0.48240	18.62849
45	17.91672	-0.53277	18.44949
46	18.18579	-0.73013	18.91593
47	21.03900	0.44027	20.59873
48	20.66971	0.39778	20.27193

* * * * * * * * * * * * * * * * * * * *

FIG. 2

APPENDIX II Extracts from the Deck Log Book of the S.T. Gondwana

APPENDIX II

EXTRACTS FROM THE DECK LOG BOOK OF THE s.t. "GONDWANA"

For the period from 0800 hrs. 20th July to 1200 hrs. 23rd July

DAY	DATE	TIME	TRUE CO.	WIND Direction	WIND Force	REMARKS
Thursday	20.7.	0800	137	S	4/5	Moderate sea and swell.
		0830	180			Ras al Hadd Lt.Ho. bearing 266 x 9,1 M. a/c to 180 (T)
		1200	180	SxW	7	Rough sea, Moderate/ Heavy head swell, shipping spray for'd
						NOON POSITION - 21 49 N 59 58 E Dist. 378 M. St. Time; 24 hrs. Spd. 15,72
		1600	180	SxW	7	Moderate head sea and swell, shipping spray for'd
		2000	180	SxW	7	Rough head sea, Moderate/heavy swell
		2400	180	SxW	7	Rough head sea, Moderate/heavy swell
Friday	21.7.	0300	180			Reduced speed
		0400	180	SW	7	Rough sea, heavy swell, shipping water for'd
		0800	180	SW	7	Rough sea, heavy swell
		1200	180	SW	8	NOON POSITION - 15 58 N. 59 45 E Dist. 351 M. St. Time 24 hrs. Spd. 14,60 Heavy sea and swell, shipping water for'd
		1600	180	SW	7	Heavy sea and swell, shipping water for'd
		1800	200			Obsvd. stella position; 14 23 N 59 55 E a/c to 200(T)
		2000	200	SW	7	Heavy sea and swell, shipping seas overall and spray for'd
		2400	200	SWxW	6/7	Heavy sea and swell, shipping sea overall and spray for'd
Saturday	22.7.	0400	200	SWxW	7	Heavy sea and swell, shipping seas and spray overall
		0800	215	SWxW	7	In D.R. Pos. 11 27 N. 58 58 E a/c 215(T)

EXTRACTS FROM THE DECK LOG BOOK OF THE s.t. "GONDWANA"

For the period from 0800 hrs. 20th July to 1200 hrs. 23rd July - continued

DAY	DATE	TIME	TRUE CO.	WIND Direction	Force	REMARKS
Saturday	22.7.	0800	215	SWxW	7	Heavy sea and swell, shipping seas and spray for'd
		1200	215	SWxW	7/8	NOON POSITION - 10 38 N 58 25 E Dist. 335 M. St. Time 24 hrs. Spd. 13,96. Heavy sea and swell, shipping water overall.
		1600	215	SW	8/9	Heavy sea and swell, shipping water overall.
		2000	215	SW	7/8	Heavy sea and swell, shipping seas and spray overall.
		2400	215	SW	6	Rough sea, Mod/heavy swell, shipping spray for'd
Sunday	23.7.	0400	215	SW	6	Rough sea, moderate swell, shipping spray
		0750	215			Increased speed
		0800	215	SW	6	Rough seas and moderate swell, shipping spray for'd
		0920	215			Increased to full sea speed
		1200	215	SW	5/6	NOON POSITION - 06 08 N 55 00 E Dist. 338 M. St. Time 24 hrs. Spd. 14,10 Rough seas and moderate swell.

EXTRACTS FROM THE DECK LOG BOOK OF THE s.t. "GONDWANA"

For the period from 1300 30th July till 2400 31st July

DAY	DATE	TIME	TRUE CO.	WIND Direction	WIND Force	REMARKS
Sunday	30.7.	1300	226	SW	6/7	Rough head seas, moderate following swell.
		1335	VAR.			Reduced speed
		1400	VAR.	SW	7	
		1600	235	SW	7	Increased to full sea speed Rough head sea, moderate swell, shipping spray for'd
		2000	VAR.	SW	7	Rough head sea, v/l shipping spray for'd
		2400	261	WSW	6	Rough sea low/moderate swell, reduced speed
Monday	31.7.	0400	261	WSW	7	Rough sea and swell, v/l pitching and shipping spray for'd
		0615	261			Reduced speed
		0800	261	W'ly	8	Very rough seas and heavy swell, v/l pitching, shipping of spray for'd
		1000	261	W'ly	8/9	
		1200	261	W'ly	8	NOON POSITION - 34 36 S 22 57 E Dist. 318 M. St. Time 24 hrs. Speed 13,25. Rough sea, heavy swell, v/l pitching heavily at times, shipping spray for'd
		1400	261	WSW	8/9	
		1600	261	SWxW	8	Rough seas, heavy swell, shipping light seas on deck, severe squalls with rain.
		2000	261	SWxW	8	Rough sea, heavy swell, pitching heavily, shipping seas on main deck.
		2145	261			Increased speed
		2330	VAR.			Increased speed
		2400	VAR.	Sw'ly	7/8	Rough sea and heavy swell, v/l rolling and pitching, shipping seas overall
Tuesday		0145	VAR.			Increased to full sea speed

EXTRACTS FROM THE DECK LOG BOOK OF THE s.t. "GONDWANA"

For the period from 1200 hrs. 11th August to 2400 hrs. 14th August

DAY	DATE	TIME	TRUE CO.	WIND Direction	WIND Force	REMARKS
Friday	11.8.	1200	000	NxW	5/6	Moderate/rough sea, low swell, v/l shipping spray for'd
		1600	VAR.	NxW	6/7	In D.R. Pos. 20 49 N 18 00 W a/c 019(T) Moderate/rough seas. Shipping spray for'd
		2000	019	NxE	7	Moderate/rough sea and swell. Shipping heavy spray for'd
		2205				Reduced speed
		2400	019	NExN	7	Rough head sea. Moderate/heavy head swell. Shipping heavy spray for'd
Saturday	12.8.	0230				D.R. pos. 23 11 N 17 07 W, a/c 035(T)
		1400	035	NexN	7	Rough seas, moderate swell
		0620				Sea moderating increased to full sea speed
		0800	035	NExN	5	Rough sea, moderate swell
		1200	035	NNE	7/8	Rough sea moderate swell. Shipping spray for'd
		1330				D.R. Pos. 25 35 N 15 31 W. a/c 038(T)
		1600	035	NNE	7	Rough sea, heavy swell, shipping spray for'd
		2000	035	NNE	7	Rough sea, moderate swell, v/l shipping heavy spray for'd
		2400	035	NNE	7	Rough head sea, moderate swell, v/l shipping spray for'd
Sunday	13.8.	0400	035	NNE	7	Rough sea, low swell, shipping spray for'd
		0800	035	N	6/7	Rough head sea, moderate swell, shipping spray for'd
		1200	035	NNE	8	Rough head sea, moderate/heavy swell, v/l shipping spray overall, and light seas on main deck

EXTRACTS FROM THE DECK LOG BOOK OF THE s.t. "GONDWANA"

For the period from 1200 hrs. 11th August to 2400 hrs. 14th August - continued

DAY	DATE	TIME	TRUE CO.	WIND Direction	Force	REMARKS
Sunday	13.8.	1600	035	N	7	Rough sea, low swell, shipping spray for'd
		2000	035	NxE	7	Rough sea, moderate swell, shipping heavy spray for'd
		2215				In position 32 04 N, 0 08 W. a/c 043(T)
		2400	043	NNE	7	Rough sea, moderate/ heavy swell, v/l shipping spray for'd
Monday	14.8.	0400	043	N	5	Moderate sea, low swell.

APPENDIX III Ordering of S.T. Gondwana data

APPENDIX III

SHIP BEHAVIOUR			ENGINE REDUCTION	WIND				SEA		
COURSE	SPEED M.G.	MOVEMENT		DIRECTION	FORCE			WAVE HT.	SWELL	CURRENT
					AHEAD	BEAM	FOLLOW			
221	16.20 17.12			sw	6 3				Japan to Gulf in Ballast	1/7 2
225	17.46 17.12			SW SW	3 3					3 4
223	17.33 17.28			SW	5 5					5 6
230 305	16.58 18.00			SW SxE	4	2				7 8
269	18.08 16.92			SSW SWxW	5	4				9 10
291 319	15.64 16.33			SW W	7	7				11 12
318	16.44 15.25			W		7 7/8				13 14
316 300	17.37 18.08			SW NW	3	4				15 16
180 180	15.72 14.60			S SW	5/6 7	7				20 21
215	13.96 14.10			SW	7 7					22 23

/Cont'd

APPENDIX III

215	16.84 16.10			SW SE	5	5				24 25
210	16.00 16.12			SE		4 3			Gulf	26 27
210	16.67 16.75			S SSE	2 2				to	28 29
226 261	17.83 13.25			NE W	8/9		5		Mediterranean	30 31
323	12.50 16.00			WSW SE	8/9		3			1 2
323	16.36 16.33			SE			4 4		-	3 4
323	16.08 16.44			SE ESE			4 3/4		Laden	5 6
323	16.87 16.96			E		2/3 2	2/3 2			7 8
323 000	16.25 16.50			SSW -	2	3				9 10
000 035	15.81 15.00			N NNE	5 7/8					11 12
040				NNE	7					13 14
										15

APPENDIX IV Facsimile Transmission Schedule for Station G.F.A.
Bracknell, England

The Transmission Schedule of Radio Facsimile Broadcast DATE 11.III.78

Name of country: United Kingdom of Great Britain and Northern Ireland

Name of centre: Bracknell

Specific area in which the broadcast is intended to be received:

In Region VI, the northern part of Region I (north of 20°N) and the western part of Region II as far as 60°E.

Technical specification:

Call sign	Frequencies	Class of emission and bandwidth	Power supplied to the antenna
GFA 21	0000 - 2400 3289.5 kHz		
GFA 22	1800 - 0600 4610 kHz	White + 400 Hz	
GFA 23	0000 - 2400 8040 kHz	F_4 Black - 400 Hz	10 Kw
GFA 24	0000 - 2400 11086.5 kHz		
GFA 25	0600 - 1800 14582 kHz		

Time GMT	Drum Speed & IOC	Chart Ident	CFFFF	Observation time	Map Area	DD	Description
0100	-	-	-	-	-	-	Radio Frequency Check
0210	120/576	FUXX KWBC	90701	1800	XX 4	12	30 hr surf/36 hr 1000-500mb
0308	120/288	AUEW EGRR	97454	0000	H	4	Prelim.anal.500mb & 1000-500mb
0345	120/288	ASXX EGRR	97401	0000	F	6	Surf. anal
0433	120/288	FSXX EGRR	97501	0000	F	6	Surf.Prog VT 24Z
0507	120/288	AUXX EGRR	97470	0000	A	10	UA anal 700mb
0518	120/288	AUXX EGRR	97450	0000	A	10	UA anal 500mb and 1000-500mb
0529	120/288	AUXX EGRR	97410	0000	A	10	UA anal 100mb
0539	120/288	AUXX EGRR	97420	0000	A	10	UA anal 200mb
0549	120/288	AUXX EGRR	97430	0000	A	10	UA anal 300mb
0610	120/288	FUXX EGRR	97550	0000	A	10	UA prog 500mb and 1000-500mb VT 24
0621	120/288	FUXX EGRR	97530	0000	A	10	UA prog 300mb VT 24
0642	120/288	FUXX EGRR	97520	0000	A	10	UA prog 200mb VT 24
0653	120/288	AUXX EGRR	97480	0000	A	10	UA anal 850mb
0711	120/288	FUXX EGRR	97510	0000	A	10	UA prog 100mb VT 24
0722	120/288	FUXX EGRR	97580	0000	A	10	UA prog 850mb VT 24
0740	120/288	FSXX EGRR	97505	0000	C	6	Surf Prog 48 & 72hr VT 24

Time GMT	Drum Speed & IOC	Chart Ident	CFFFF	Observation time	Map Area	DD	Description
0750	120/288	FUXX EGRR	97570	0000	A	10	UA Prog 700mb VT 24
0811	120/288	AXNT EGRR	97490	0000	G	6	North Atl.Wave anal.
0817	120/288	FXNT EGRR	97590	0000	G	6	North Atl.Wave prog 24 hr VT 24
0830	-	-	-	-	-	-	General Notices
0853	120/288	ASXN EGRR	97408	0000	D	8	Surf.Anal.Circumpolar
0919	120/288	AUXN EGRR	97458	0000	D	8	UA anal 500mb Circumpolar
0945	120/288	ASXX EGRR	97402	0600	F	6	Surf.anal.
0952	120/288	FXNT EGRR	97592	0000	G	6	North Atl Wave prog 48 hr VT24
1001	120/576	FUXX KWBC	90727	0000	XX 11	14	UA prog 500mb 48hr VT 24
1017	120/576	FUXX KWBC	90734	0000	XX 10	12	UA prog 500mb 36 hr VT 12
1036	120/288	FSXX EGRR	97502	0600	F	6	Surf.prog VT 06
1043	120/576	FUXX KWBC	90728	0000		13	UA prog 500 72 hr VT 24
1101	120/576	FUXX KWBC	90729	0000		13	Ext.prog. 108 hrs
1117	120/576	FUXX KWBC	90739	-	J	12	Monthly forecast (Bi-monthly)
1131	120/576	FUXX KWBC	90740	-	-	12	5-day mean 700 mb
1146	120/576	FUXX KWBC	90738	0600	XX 4	12	30hr surf/36 hr 1000-500mb
1202	120/576	FUXX KWBC	90731	0000		13	Ext Prog 132 hrs
1300	-	-	-	-	-	-	Radio frequency check
1333	120/576	ANXX EGRR	97495		F	10	Nephanalysis
1508	120/288	AUEU EGRR	97456	1200	H	4	Prelim anal 500mb and 1000-500mb
1545	120/288	ASXX EGRR	97403	1200	F	6	Surf.anal

Time GMT	Drum Speed & IOC	Chart Ident	CFFFF	Observation time	Map Area	DD	Description
1636	120/288	FSXX EGRR	97503	1200	F	6	Surf.prog. VT 12
1707	120/288	AUXX EGRR	97472	1200	A	10	UA anal 700mb
1718	120/288	AUXX EGRR	97452	1200	A	10	UA anal 500mb and 1000-500mb
1729	120/288	AUXX EGRR	97421	1200	A	10	UA anal 100mb
1739	120/288	AUXX EGRR	97422	1200	A	10	UA anal 200mb
1749	120/288	AUXX EGRR	97432	1200	A	10	UA anal 300mb
1810	120/288	FUXX EGRR	97552	1200	A	10	UA prog 500mb and 1000-500mb VT 12
1821	120/288	FUXX EGRR	97532	1200	A	10	UA prog 300mb VT 12
1842	120/288	FUXX EGRR	97522	1200	A	10	UA prog 200mb VT 12
1853	120/288	AUXX EGRR	97482	1200	A	10	UA anal 850mb
1911	120/288	FUXX EGRR	97512	1200	A	10	UA prog 100mb VT 12
1922	120/288	FUXX EGRR	97582	1200	A	10	UA prog 850mb VT 12
1950	120/288	AUXX EGRR	97472	1200	A	10	UA prog 700mb
2011	120/288	AXNT EGRR	97491	1200	G	6	North Atl.Wave Anal
2017	120/288	FXNT EGRR	97591	1200	G	6	North Atl.Wave anal 24 hr VT 12
2053	120/576	AUXX KWBC	90760	1200	XX 11	14	UA anal 500mb
2145	120/288	ASXX EGRR	97404	1800	F	6	Surf.Anal.
2152	120/288	FXNT EGRR	97593	1200	G	6	North Atl.Wave Prog 48 hr VT 12
2201	120/576	FUXX KWBC	90773	1200	XX 11	14	UA prog 500mb 48hr VT 12
2233	120/288	FSXX EGRR	97504	1800	F	6	Surf.Prog. VT18
2330	120/576	FUXX KWBC	90776	1200	XX 10	12	UA prog 500mb 36hr VT 00
2345	120/576	FUXX KWBC	90778	1200	XX 11	14	500mb 72 hr prog VT 12

Map Areas

All projections are polar stereographic

Map A

Scale: 1 : 20,000,000 at 60°N
Area: 48°N 145°W : 32°N 68°E
24°N 69°W : 15°N 10°E

Map D

Scale: 1 : 30,000,000 at 60°N
Area: 29°N 155°W : 28°N 63°E
08°N 85°W : 08°N 06°W

Map F

Scale: 1 : 20,000,000 at 60°N
Area: 69°N 111°W : 37°N 50°E
34°N 55°W : 19°N 10°E

Map G

Scale: 1 : 20,000,000 at 60°N
Area: 38°N 114°W : 60°N 32°E
19°N 77°W : 30°N 09°W

Map H

Scale: 1 : 20,000,000 at 60°N
Area: 72°N 35°W : 46°N 32°E
41°N 35°W : 29°N 04°E

XX-4 (U.S chart)

Scale: 1 : 40,000,000
Area: 26.5°N 138°E : 26°N 14°W
09°N 163°W : 09°N 73°W

XX-10 (U.S chart)

Scale: 1 : 40,000,000
Area: 01°N 31.5°W : 01°N 128.5°W
14°N 29.5°E : 14°N 171°E

XX-11 (U.S chart)

Scale: 1 : 40,000,000
Area: 01°N 31.5°W : 01°N 128.5°W
11°N 37°E : 10.5°N 162.5°E

Map Z 1 : 50,000,000
42°N 60°W : 66°N 90°E
20°N 20°W : 30°N 20°E

Notes 1. Time of broadcast of Washington WMC charts is dependent upon time of receipt at Bracknell from Washington.

2. A schedule of up to date contents of the transmission is broadcast each Thursday at 0830 GMT

APPENDIX V Steering of Depressions (Case Studies)

MONTH Jan'80 DATE	DAY 1 ms^{-1}	DIR^o	DAY 2 ms^{-1}	DIR^o	DAY 3 ms^{-1}	DIR^o	DAY 4 ms^{-1}	DIR^o	DAY 5 ms^{-1}	DIR^o
$V_{surface}$ Wave	16.1	043	13.1	070	4.1	120	3.8	090	3.4	125
Cant of Trough - λ	400 Km		175 Km		Zero		Zero		Zero	
U_{500}	31.7		28.5		21.7		22.3		22.1	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	17.2	047	14.0	070	7.2	085	7.8	060	7.6	var
$\chi_s \sim U'^{1st/6th}_{500}$	1.1	04	0.9	00	3.1	35	4.0	30	4.2	-
χ_s wave	9.1	062	16.8	051	7.5	014	6.2	013	10.1	300
Cant of Trough - λ	980 Km		300 Km		120 Km		Zero		Zero	
U_{500}	22.8		28.0		21.7		23.0		21.6	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	8.3	068	13.5	057	7.2	014	8.5	000	7.1	340
$\chi_s \sim U'^{2nd/7th}_{500}$	0.8	06	3.3	06	0.3	00	2.3	13	3.0	40
χ_s wave	10.8	079	29.3	026	3.8	002	3.7	004	Stationary	-
Cant of Trough - λ	760 Km		600 Km		540 Km		Zero		Zero	
U_{500}	25.0		40.5		22.3		22.3		15.0	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	10.5	088	26.0	040	7.8	015	7.8	030	0.5	
$\chi_s \sim U'^{6th/11th}_{500}$	0.3	09	3.3	14	4.0	13	4.1	26	0.5	
χ_s wave	28.1	052	17.9	023	23.0	027	10.2	078	5.1	082
Cant of Trough - λ	550 Km		700 Km		620 Km		100 Km		Zero	
U_{500}	42.4		32.4		34.5		28.8		24.8	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	27.9	052	17.9	023	20.0	023	14.3	059	10.3	065
$\chi_s \sim U'^{10th/18th}_{500}$	0.2	00	0.0	00	3.0	04	4.1	19	5.2	17
χ_s wave	5.3	060	4.8	090	4.7	080	Stationary		2.0	170
Cant of Trough - λ	450 Km		410 Km		390 Km		Zero		Zero	
U_{500}	18.7		20.8		21.9		22.5		24.5	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	4.2	050	6.3	105	7.4	110	8.0		10.0	100
$\chi_s \sim U'^{15th/19th}_{500}$	1.1	10	1.5	15	2.7	30	8.0	-	8.0	70

MONTH Jan '80 DATE	DAY 1 ms^{-1}	DIR^{o}	DAY 2 ms^{-1}	DIR^{o}	DAY 3 ms^{-1}	DIR^{o}	DAY 4 ms^{-1}	DIR^{o}	DAY 5 ms^{-1}	DIR^{o}
$V_{surface}$ Wave	8.6	085	10.0	040	19.9	095	8.2	170	Stationary	
Cant of Trough - λ	500 Km		850 Km		1700 Km		Zero		Zero	
U_{500}	20.3		23.5		33.6		26.6		23.5	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	5.8	070	9.0	048	19.1	060	12.1	090	9.0	090
$V_s \sim U'^{\,20th/25th}_{500}$	2.8	15	1.0	8	0.8	35	12.1	80	9.0	-
V_s wave	8.4	010	4.7	095	4.1	015	9.4	092	11.7	041
Cant of Trough - λ	1200		400		Zero		Zero		Zero	
U_{500}	23.9		16.5		22.7		17.9		15.0	
$\bar{U}_{500}$	14.5		14.5		14.5		14.5		14.5	
U'_{500}	9.4	015	2.0	080	8.2	080	3.4	040	0.5	000
$V_s \sim U'^{\,24th/29th}_{500}$	1.0	5	2.7	15	4.1	65	6.0	52	11.2	41
V_s wave										
Cant of Trough - λ										
U_{500}										
$\bar{U}_{500}$										
U'_{500}										
$V_s \sim U'_{500}$										
V_s wave										
Cant of Trough - λ										
U_{500}										
$\bar{U}_{500}$										
U'_{500}										
$V_s \sim U'_{500}$										
V_s wave										
Cant of Trough - λ										
U_{500}										
$\bar{U}_{500}$										
U'_{500}										
$V_s \sim U'_{500}$										

MONTH Feb '80 DATE	DAY 1 ms^{-1}	DIR°	DAY 2 ms^{-1}	DIR°	DAY 3 ms^{-1}	DIR°	DAY 4 ms^{-1}	DIR°	DAY 5 ms^{-1}	DIR°
$V_{surface}$ Wave	23	052	20.4	047	3.8	172	10.2	061		
Cant of Trough - λ	600 Km		650 Km		100 Km		Zero			
U_{500}	39.1		36.0		23.2		18.2			
$\bar{U}_{500}$	15.1		15.1		15.1		15.1			
U'_{500}	24.0	052	20.9	049	8.1	095	3.1	095		
$V_s \sim U'^{1-5}_{500}$	1.0	00	0.5	02	4.3	77	7.1	34		
V_s wave	15.3	054	23.6	041	3.6	037	8.4	009	2.7	295
Cant of Trough - λ	1000 Km		270 Km		110 Km		Zero		Zero	
U_{500}	30.9		36.6		23.8		20.7		20.0	
$\bar{U}_{500}$	15.1		15.1		15.1		15.1		15.1	
U'_{500}	15.8	056	21.5	049	8.7	057	5.6	042	4.9	005
$V_s \sim U'^{5-10}_{500}$	0.5	02	2.1	08	5.1	20	5.6	33	4.9	70
V_s wave	11.5	042	17.7	078	21.0	050	10.6	034	2.0	Stat
Cant of Trough - λ	300 Km		820 Km		600 Km		200 Km		Zero	
U_{500}	32.1		41.1		41.1		30.1		25.8	
$\bar{U}_{500}$	15.1		15.1		15.1		15.1		15.1	
U'_{500}	17.0	067	26.0	090	26.0	072	15.0	048	10.7	041
$V_s \sim U'^{7-11}_{500}$	5.5	25	8.3	12	5.0	22	4.4	14	8.7	-
V_s wave	17.5	095	21.0	053	7.5	017	20.0	355		
Cant of Trough -	540 Km		320 Km		Zero		Zero			
U_{500}	31.9		34.6		19.3		20.2			
$\bar{U}_{500}$	15.1		15.1		15.1		15.1			
U'_{500}	16.8	092	19.5	052	4.2	040	5.1	030		
$V_s \sim U'^{13-17}_{500}$	0.7	03	1.5	01	3.3	23	14.9	35		
V_s wave	21.1	049	32.5	015	4.2	029	3.1	032		
Cant of Trough -	Unclear		Unclear		Zero		Zero			
U_{500}	41.9		39.8		29.4		30.4			
$\bar{U}_{500}$	15.1		15.1		15.1		15.1			
U'_{500}	26.8	061	24.7	055	14.3	053	15.3	061		
$V_s \sim U'^{17-21}_{500}$	5.7	12	7.8	40	10.1	14	12.2	29		

MONTH Feb '80 DATE	DAY 1 ms^{-1}	DIR°	DAY 2 ms^{-1}	DIR°	DAY 3 ms^{-1}	DIR°	DAY 4 ms^{-1}	DIR°	DAY 5 ms^{-1}	DIR°
$V_{surface}$ Wave	15.0	044	16.2	047	17.5	028	8.2	027		
Cant of Trough - λ	500 Km		300 Km		Zero		Zero			
U_{500}	30.2		30.4		28.2		19.1			
$\bar{U}_{500}$	15.1		15.1		15.1		15.1			
U'_{500}	15.1	044	15.3	050	13.1	047	4.0	062		
$V_s \sim U'^{20-24}_{500}$	0.1	00	0.9	03	4.4	19	4.2	35		
V_s wave	18.1	047	21.0	028	18.0	042	7.2	Stationary		
Cant of Trough - λ	400 Km		250 Km		Zero		Zero			
U_{500}	33.7		30.1		24.6		20.9			
$\bar{U}_{500}$	15.1		15.1		15.1		15.1			
U'_{500}	18.6	045	15.0	040	9.5	030	5.8	038		
$V_s \sim U'^{24-25}_{500}$	0.5	02	6.0	12	8.5	12	1.4	-		
V_s wave										
Cant of Trough - λ										
U_{500}										
$\bar{U}_{500}$										
U'_{500}										
$V_s \sim U'_{500}$										
V_s wave										
Cant of Trough - λ										
U_{500}										
$\bar{U}_{500}$										
U'_{500}										
$V_s \sim U'_{500}$										
V_s wave										
Cant of Trough - λ										
U_{500}										
$\bar{U}_{500}$										
U'_{500}										
$V_s \sim U'_{500}$										

MONTH June '80 DATE	DAY 1 ms^{-1}	DIR°	DAY 2 ms^{-1}	DIR°	DAY 3 ms^{-1}	DIR°	DAY 4 ms^{-1}	DIR°	DAY 5 ms^{-1}	DIR°
$\underset{\sim}{V}_{surface}$ Wave	15.3	086	9.8	047	12.1	048	9.5	095		
Cant of Trough - λ	650 Km		600 Km		400 Km		Zero			
U_{500}	20.8		13.0		14.5		10.5			
$\bar{U}_{500}$	8.2		8.2		8.2		8.2			
U'_{500}	12.6	084	4.8	028	6.3	041	2.3	087		
$\underset{\sim}{V}_s \sim U'^{4-8}_{500}$	2.7	02	5.0	19	5.8	07	7.2	08		
$\underset{\sim}{V}_s$ wave	15.7	070	11.2	049	21.0	035	9.6	047	14.8	010
Cant of Trough - λ	680 Km		750 Km		700 Km		300 Km		Zero	
U_{500}	28.0		20.6		11.0		10.0		9.0	
$\bar{U}_{500}$	8.2		8.2		8.2		8.2		8.2	
U'_{500}	19.8	090	12.4	052	19.2	037	1.8	045	0.8	005
$\underset{\sim}{V}_s \sim U'^{9-14}_{500}$	4.1	20	1.2	03	1.8	02	7.8	02	14.0	05
$\underset{\sim}{V}_s$ wave	11.7	021	12.5	037	9.1	043	14.8	054	13.3	052
Cant of Trough - λ	320 Km		400 Km		300 Km		150 Km		Zero	
U_{500}	17.4		19.7		13.3		12.0		12.0	
$\bar{U}_{500}$	8.2		8.2		8.2		8.2		8.2	
U'_{500}	9.2		11.5		5.1	032	3.8	042	3.8	070
$\underset{\sim}{V}_s \sim U'^{14-19}_{500}$	2.5	02	1.0	01	4.0	11	11.0	12	9.5	18
$\underset{\sim}{V}_s$ wave	15.5	037	13.3	078	16.0	108	10.3	079		
Cant of Trough - λ	750 Km		400 Km		Zero		Zero			
U_{500}	23.0		20.0		20.0		9.8			
$\bar{U}_{500}$	8.2		8.2		8.2		8.2			
U'_{500}	14.8	043	11.8	070	11.8	121	1.6	092		
$\underset{\sim}{V}_s \sim U'^{20-24}_{500}$	0.7	06	1.5	08	4.2	13	8.7	13		
$\underset{\sim}{V}_s$ wave	9.7	039	10.2	048	Stationary		Stationary		Stationary	
Cant of Trough - λ	250 Km		350 Km		100 Km		Zero		Zero	
U_{500}	20.0		21.0		10.0		10.0		10.0	
$\bar{U}_{500}$	8.2		8.2		8.2		8.2		8.2	
U'_{500}	11.8	046	11.8	060	1.8		1.8		1.8	
$\underset{\sim}{V}_s \sim U'^{25-30}_{500}$	2.1	07	1.6	12	1.8	-	1.8	-	1.8	-

MONTH July '80 DATE	DAY 1 ms^{-1}	DIR°	DAY 2 ms^{-1}	DIR°	DAY 3 ms^{-1}	DIR°	DAY 4 ms^{-1}	DIR°	DAY 5 ms^{-1}	DIR°
$\chi_{surface}$ Wave	15.3	053	16.9	061	8.9	058	5.8	074		
Cant of Trough - λ	350 Km		430 Km		300 Km		Zero			
U_{500}	23.0		25.0		18.0		11.0			
$\bar{U}_{500}$	7.8		7.8		7.8		7.8			
U'_{500}	15.2	052	17.2	065	10.2	064	3.2	064		
$\chi_s \sim U'^{1-5}_{500}$	0.1	01	0.3	04	1.3	06	2.6	10		
χ_s wave	7.9	061	8.6	072	12.1	034	5.3	040	6.5	024
Cant of Trough - λ	300 Km		400 Km		220 Km		Zero		Zero	
U_{500}	17.0		16.8		15.5		10.0		8.0	
$\bar{U}_{500}$	7.8		7.8		7.8		7.8		7.8	
U'_{500}	9.2	066	9.0	074	7.7	039	2.2	025	0.2	010
$\chi_s \sim U'^{6-11}_{500}$	1.3	05	0.4	02	4.4	05	3.1	15	6.3	14
χ_s wave	6.4	053	5.1	048	8.3	042	14.4	060	11.4	082
Cant of Trough - λ	200 Km		310 Km		50 Km		Zero		Zero	
U_{500}	14.0		13.0		14.0		15.0		15.0	
$\bar{U}_{500}$	7.8		7.8		7.8		7.8		7.8	
U'_{500}	6.2	049	5.2	046	6.2	050	7.2	068	7.2	055
$\chi_s \sim U'^{13-18}_{500}$	0.2	04	0.1	02	2.1	08	7.2	08	4.2	27
χ_s wave	14.7	058	7.7	063	8.3	050	10.2	055	4.5	060
Cant of Trough - λ	250 Km		600 Km		200 Km		100 Km		Zero	
U_{500}	21.3		14.0		12.0		11.0		8.0	
$\bar{U}_{500}$	7.8		7.8		7.8		7.8		7.8	
U'_{500}	13.5	062	6.2	063	4.2	072	3.2	063	0.2	045
$\chi_s \sim U'^{18-23}_{500}$	1.2	04	1.5	00	4.1	22	7.0	08	4.3	15
χ_s wave	7.8	055	11.4	020	13.1	040				
Cant of Trough - λ	350 Km		200 Km		Zero					
U_{500}	16.4		17.2		12.0					
$\bar{U}_{500}$	7.8		7.8		7.8					
U'_{500}	8.6	055	9.4	021	4.2	021				
$\chi_s \sim U'^{25-28}_{500}$	0.8	00	2.0	01	8.9	19				

APPENDIX VI Facsimile information for ship-based weather routeing : 6.4.3

(pages 172-184)


HM
1025
HQ
1037
HN
1043
LL
1015
994
1000
08
16
60
32
24
40
50°
40°
30°
20°
10°
0°
9 FEB. 1981 0000 GMT.

576
60
546
40
50
50°
30°
20°
10
40
576
9 FEB 1981 500 MB 0000 GMT

TEXT BOUND INTO

THE SPINE


KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT
WAVE ANALYSIS 1200 GMT Tuesday, 10-2-1981
LEGEND
Direction
Significant wave height in metres
Sea
Direction
Significant wave height in metres
Swell
Front
L H Centre of low/high pressure
Limit of all known ice
Limit of pack ice

...ANDS ME... ...SCH INSTITU...
...5 1200GMT FEB 9th – 13th inc
COMPOSITE SEA STATE
...wave height in metres } Sea
...wave height in metres } Swell
...ow / high pressure
...known ice
...pack ice
DAY 1 MON 9
DAY 2 TUES 10
DAY 3 WED 11
DAY 4 THU 12
DAY 5 FRI 13

965
LA
1000
LL
1012
LZ
1015
HN40
1045
STAT.
10 FEB. 1981 0600 GMT

10 FEB 1981 500MB 0000GMT


KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT
WAVE ANALYSIS 1200 GMT Tuesday, 10-2-1981
LEGEND
Direction
Significant wave height in metres
Sea
Direction
Significant wave height in metres
Swell
Front
L H Centre of low / high pressure
Limit of all known ice
Limit of pack ice

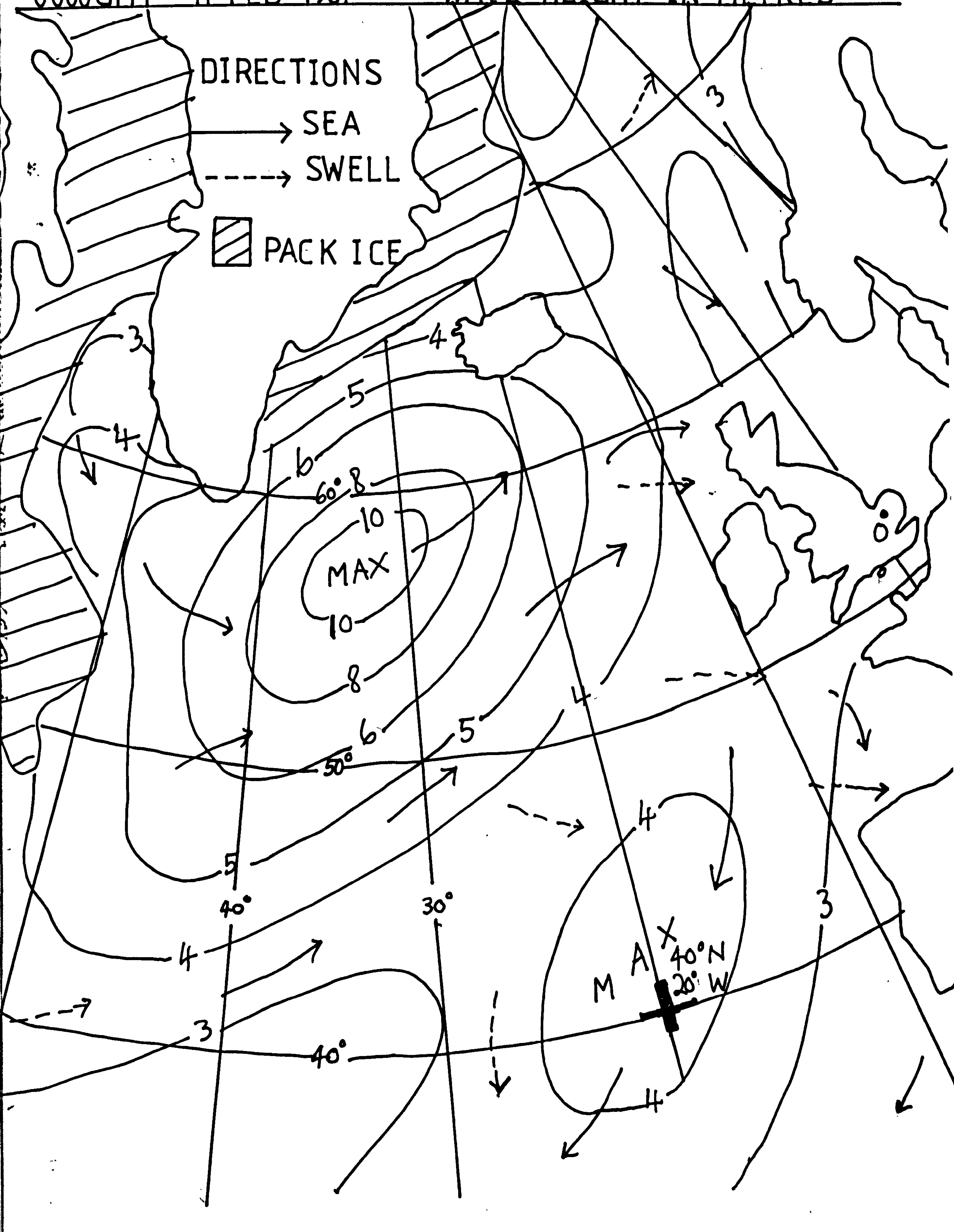
11 FEB 1981 0600G.M.T.

11 FEB 1981 500 MB 0000GMT.


KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT
WAVE ANALYSIS 1200 GMT Wednesday 11-2-1981
LEGEND
Direction
Significant wave height in metres
Sea
Direction
Significant wave height in metres
Swell
Front
L H Centre of low / high pressure
Limit of all known ice
Limit of pack ice
80
70
60
50
40
30
20
90
20
80

COMBINED SEA AND SWELL 48 HR PROG VALID

0000GMT 11 FEB 1981 WAVE HEIGHT IN METRES




KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT
WAVE ANALYSIS 1200 GMT Thursday 12-2-'81
LEGEND
Direction
Significant wave height in metres
Sea
Direction
Significant wave height in metres
Swell
Front
L H Centre of low/high pressure
Limit of all known ice
Limit of pack ice
H
H


KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT
WAVE ANALYSIS 1200 GMT friday 13-2-81
LEGEND
Direction
Significant wave height in metres
Sea
Direction
Significant wave height in metres
Swell
Front
L H Centre of low/high pressure
Limit of all known ice
Limit of pack ice
90
20
80


ICE COVER
for PERIOD.
2
6
10
12
14

APPENDIX VII Letter received from Capt. Max Dobbert

Capt.Max Dobbert
Korndiek 14
2112 Jesteburg
West-Germany

At Sea, June 29, 1977

Captain R. Motte
Senior Lecturer in Meteorology
Plymouth Polytechnic
Plymouth England

Dear Sir,

after having studied" Weather Routeing of Ships ", I feel compelled to say "Thank you" for this fine book, a specimen copy I have purchased last year,when I was home. Marvellous your instructions and explanations.At present I am in command of the Tanker "Ivory Sun" (DWT 100,000 tons) en route from Dumai via Tanjung Santan (Borneo) towards Long Beach Cal.

The first experience I received was with an american Owner or more correct :operator of the vessel,Liberian flag,50,000 tons DWT tanker in the Pacific Weather Routeing from San Francisco,Cal. 1962 , On that vessel I was in command for 5½ years in the tanker trade between Long Beach-Persian Gulf. In 1976 I was weatherrouted by the german Seewetteramt ,a vessel -20,000 tons DWT - engaged in the Emden (Germany) -great Lakes run,there crossing the Atlantic from Pentland Firth towards Belle Isle Strait in 4½ days - speed abt.16 knots.

I only wish,that your fine book will find a wide distribution among also younger Masters-the one I relieved on this vessel in Japan still sticks to the system to planning his course according to the pilotchart for the respective month. On this vessel,when I was in command also last year in November/December ,we sailed from Puget Sound towards Singapore on the Great Circle route (not weather routed,but following the daily weather reports),and experienced ,that the most lows passed southof our position,two lows northward,and our vessel was only rolling due to swell,but no pounding ,and no water on deck,we were in ballast.

With regardto myself, I am at sea since 1925,brought up with the Flying"P"-Line (6 times round Cape Hoorn) and-thanks God- with good health still navigating .(My age 67).

With best wishes

respectfully
Max Dobbert
Max Dobbert